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STEAM-BOILER

EXPLOSIONS.

IN THEORY AND IN PRACTICE.

BY

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PREFACE.

THIS little treatise on Steam-Boiler Explosions had its origin in the following circumstances:

In the year 1872 the Author received from the Secretary of the Treasury of the United States a communication in which he was requested to prepare, for the use of the Treasury Department, a report on the causes and the conditions leading to the explosions of steam-boilers, and began the preparation of such a report, in which he proposed to incorporate the facts to be here presented.

The pressure of more imperative duties became so heavy, immediately after the receipt of that request, that the work was interrupted before it had been more than fairly begun. An examination had been made of the records of earlier legislation, in the United States and in foreign countries, relating to the regulation of the use of steam boilers; and an investigation was begun tracing the experimental and scientific development of the later theories of explosion. The work was never entirely given up, however, and the notes collected from time to time were added to those then obtained, and have since formed the basis of later lectures by the Author on this subject.

In the year 1875, the Author, then a member of a commission formed by the government to investigate the subject, was asked by the Cabinet officer having direction of

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the matter to accept the chairmanship of the commission and to give his time to the subject under investigation. For sufficient reasons he was unwilling to undertake the work, and an older and wiser head was appointed. His connection with that commission, however, further stimulated that interest which he had always felt in the matter, and led to the study of the subject from new standpoints. It seemed evident, from what was learned there and elsewhere, in the experimental explosion of steam-boilers, that, usually, the only unknown element in such cases was the magnitude of the stock of energy stored in a boiler before explosion, and the extent to which it was applied, at the instant of the catastrophe, to the production of disastrous effects.

The calculation of the quantity of energy stored and available was undertaken and partly completed, and then was interrupted by the decease of a most efficient and helpful assistant; was again undertaken, later, by two earnest friends and pupils of the Author, and was finally completed in the form in which it will be found presented in the following pages.

Thus, the subject is one which the Author has endeavored at several different periods in the course of his work to take up and reduce, if possible, to a consistent theoretical and practically applicable form. On each occasion his labors were interrupted before they were fairly begun. It cannot be said that they are now completed; but enough has been done to permit the presentation of a systematic outline of this subject. Probably no subject within the whole range of the practice of the engineer has demanded or has received more attention than this; and probably no such subject has been less satisfactorily developed in

theory and less thoroughly investigated experimentally than this. But some good work has now been done, and well done, during late years, and the experience of the steam-boiler insurance and inspection companies has fortunately served an excellent purpose in showing that the element of mystery commonly exists only in the imagination of writers having more poetry than logic in their composition, and that the causes of accident are wholly preventible and controllable.

The importance of this matter can hardly be overestimated. When, as estimated by the late Mr. G. H. Babcock, there were, in the United States, in 1893, 10,000,000 horse-power, distributed among 100,000 steam-boilers, and when, as reported by the insurance companies, there were discovered over 1,000 new and dangerous defects every month by the company and risks paid on 20 explosions, it may well be imagined that this subject is rated by the engineer the most important with which he has to deal. It is, however, encouraging to note that the probably 15,000 or 20,000 dangerous defects annually detected—by explosion or inspection—are principally, and the 250 to 300 explosions per annum, in the United States alone, substantially all of shell boilers, and that the "sectional" or "safety" boilers are rapidly becoming substituted for the older types, with resulting diminution of danger.

The 52 boilers, of 25.000 collective rated horse-power exhibited at the Exposition at Chicago, in 1893, were nearly all of the modern type.

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INTRODUCTION.

STEAM BOILER EXPLOSIONS.

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INTRODUCTION.*

HEAT-ENERGY OF STEAM AND WATER.

1. **The Stored Energy of Steam or Water,** confined under a pressure so far exceeding atmospheric as to make the boiling point and the temperature of the fluid considerably greater than is observed where water becomes vapor in the open air, is often of such considerable amount as to make its determination a matter of real importance. A steam-boiler explosion is but the effect of causes which permit the transformation of a part of the heat-energy stored in the vessel into mechanical energy, and the application of that energy to the production of results which are often terribly impressive and disastrous. The first step, therefore, in any proposed scheme of study of this important and attractive subject is, naturally, an examination of the conditions under which energy is stored, and of the magnitude of the forces and energies latent in steam and in water when confined under high pressure. The first attempt to calculate the amount of energy latent in steam, and capable of greater or less utilization in expansion by

*Mainly from a paper by the Author " On Steam Boilers as Magazines of Explosive Energy." Trans. Am. Soc. Mech. Engrs., 1884.

explosion, was made by Mr. George Biddle Airy,* the Astronomer Royal of Great Britain, in the year 1863, and by the late Professor Rankine† at about the same time.

2. **Formulas** giving the energy stored in steam and in water are now well established. In Rankine's paper, just referred to, for example, there were given expressions for the calculation of the energy and of the ultimate volumes assumed during the expansion of water into steam, as follows, in British and in Metric measures:

$$U=\frac{772\,(T-212^2}{T+1134.4});\qquad U_m=\frac{423.55\,(T-100)^2}{T+648};$$

$$V=\frac{36.76\,(T-212)}{T+1134.4};\qquad V_m=\frac{2.29\,(T-100)}{T+648}.$$

These formulas give the energy in foot-pounds and kilogrammeters, and the volumes in cubic feet and cubic meters. They may be used for temperatures not found in the tables to be given, but, in view of the completeness of the latter, it will probably be seldom necessary for the engineer to resort to them.

The quantity of work and of energy which may be liberated by the explosion, or utilized by the expansion, of a mass of mingled steam and water has been shown by Rankine and by Clausius, who determined this quantity almost simultaneously, to be easily ex-

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*"Numerical Expression of the Destructive Energy in the Explosions of Steam Boilers," Phil. Mag., Nov. 1863.

† "On the Expansive Energy of Heated Water"; ibid.

pressed in terms of the two temperatures between which the expansion takes place.

When a mass of steam, originally dry, but saturated, so expands from an initial absolute temperature, T_1, to a final absolute temperature, T_2, if J is the mechanical equivalent of the unit of heat, and H is the measure, in the same units, of the latent heat per unit of weight of steam, the total quantity of energy exerted against the piston of a non-condensing engine, by unity of weight of the expanding mass is, as a maximum,

$$U = JT_2 \left(\frac{T_1}{T_2} - 1 - \text{hyp. log.} \frac{T_1}{T_2} \right) + \frac{T_1 - T_2}{T_1} H \ldots (A.$$

This equation was published by Rankine a generation ago.*

When a mingled mass of steam and water similarly expands, if M represents the weight of the total mass and m is the weight of the steam alone, the work done by such expansion will be measured by the expression,

$$U = MJT_2 \left(\frac{T_1}{T_2} - 1 - \text{hyp. log.} \frac{T_1}{T_2} \right) + m \frac{T_1 - T_2}{T_1} H \ldots (B)$$

This equation was published by Clausius in substantially this form.†

It is evident that the latent heat of the quantity m, which is represented by mH, becomes zero when the mass consists solely of water, and that the first term of

* Steam Engine and Prime Movers, p. 387.

† Mechanical Theory of Heat, Browne's Translation, p. 283.

the second member of the equation measures the amount of energy of heated water which may be set free, or converted into mechanical energy, by explosion. The available energy of heated water, when explosion occurs, is thus easily measurable.

As has already been stated, this method was first applied by Rankine to the determination of the available energy of heated water for several selected temperatures and pressures. It had long been the intention of the Author to ascertain the magnitude of the quantities of energy residing, in available form, in both steam and water, for the whole usual range of temperatures and pressures familiar to the engineer, and also to carry out the calculations for temperatures and pressures not yet attained, except experimentally, but which are likely to be reached in the course of time, as the constantly progressing increase now observable goes on. The maximum attainable, in the effort to increase the efficiency of the steam engine and in the application of steam to new purposes, cannot be to-day predicted, or even, so far as the writer can see, imagined. High pressures like those adopted by Perkins and by Alban may yet be found useful. It was therefore proposed to carry out the tables to be constructed far beyond the limit of present necessities.

It was further proposed to ascertain the weights of steam and of water contained in each of the more common forms of steam boiler, and to determine the total and relative amounts of energy confined in each under the usual conditions of working in every-day practice,

and thus to ascertain their relative destructive power in case of explosion.

At the commencement of this work, the Author employed the late Mr. W. G. Cartwright, as computer, and, with his aid, prepared tables extending from 50 pounds per square inch to 100 at intervals of ten pounds, up to 250 with intervals of 25 pounds, then 300, and up to 1000 pounds per square inch by 100 pounds, and with larger intervals up to 10,000 and 20,000 pounds. The available energy of the heated water was computed, the energy obtainable from the so-called "latent heat," and their sum, *i. e.*, the available energy of steam per unit of weight. In the course of this work, each figure was calculated independently by two computers, and thus checked. As a further check, the figures so obtained were plotted, and the curve representing the law of their variation was drawn. This was a smooth curve of moderate curvature and an incorrect determination was plainly revealed, and easily detected, by falling outside the curve. Three curves were thus constructed, which will be given later: (1) The Curve of Available Energy of Heated Water; (2) The Curve of Available Energy of Latent Heat; (3) the Curve of Available Energy of Steam. The second of these curves presents an interesting peculiarity which will be pointed out when studying the forms of the several curves and the tables of results.

The work was interrupted by more pressing duties, and was finally resumed in the spring of 1884 and com-

pleted in the form now presented. The computers of the more complete tables here given were Messrs. Ernest H. Foster, and Kenneth Torrance, who, pursuing the same method as was originally adopted for the earlier computations, have revised the whole work, recalculating every figure, extending the tables by interpolation, and carrying them up to a still higher pressure than was originally proposed. The tables here presented range from 20 pounds per square inch, (1.4 kgs. per sq. cm.) up to 100,000 per square inch (7,030.83 kgs. per sq. cm.) the maximum probably falling far beyond the range of possible application, its temperature exceeding that at which the metals retain their tenacity, and, in some cases, exceeding their melting points. These high figures are not to be taken as exact. The relation of temperature to pressure is obtained by the use of Rankine's equation, of which it can only be said that it is wonderfully exact throughout the range of pressures within which experiment has extended, and within which it can be verified. The values estimated and tabulated are probably quite exact enough for the present purposes of even the military engineer and ordnance officer. The form of the equation, and of the curve representing the law of variation of pressure with temperature, indicates that, if exact at the familiar pressures and temperatures, it is not likely to be inexact at higher pressures. The curve. at its upper extremity becomes nearly rectilinear.

3. **The Calculated Energy of Water and Steam** are given in the table which follows, and which presents

the values of the pressures in pounds per square inch above a vacuum, the corresponding reading of the steam-gauge (allowing a barometric pressure of 14.7 pounds per square inch), and the same pressures reckoned in atmospheres, the corresponding temperatures as given by the Centigrade and the Fahrenheit thermometers, and as reckoned both from the usual and the absolute zeros. The amount of the explosive energy of a unit weight of water, of the latent heat in a unit weight of steam, and the total available heat-energy of the steam, are given for each of the stated temperatures and pressures throughout the whole range in British measures, atmospheric pressures being assumed to limit expansion. The values of the latent heats are taken from Regnault, for moderate pressures, and are calculated for the higher pressures, beyond the range of experiment, by the use of Rankine's modification of Regnault's formula.

TOTAL AVAILABLE ENERGY IN WATER AND STEAM.

Pressure above a vacuum in pounds per sq. inch.	Same pressure as indicated by steam gauge, allowing 14.7 lbs. for atmospheric pressure.	Absolute pressure in atmospheres.	Number of British Thermal units required for the evaporation of one pound of water, known as latent heat of evaporation, H.	Temperature in degrees Fahrenheit of the steam and of the water from which it is evaporated.	Temperature in degrees Centigrade of the steam and of the water from which it is evaporated.	Corresponding absolute temperature in degrees Fahrenheit.	Corresponding absolute temperature in degrees Centigrade.	Amount of energy contain'd in one pound of water which may be liberated by explosion or expansion to 212° Fahr.	Corresponding amount of energy contained in the latent heat of evaporation.	Total amount of energy contained in one pound of steam at corresponding temperatures and pressures.
20	5.3	1.36	954.415	227.9	108.8	689.0	382.8	145.9	16872.6	17018.8
25	10.3	1.70	945.825	240.0	115.5	701.2	389.5	439.7	29156.8	29596.5
30	15.3	2.04	938.925	250.2	121.2	711.4	395.2	813.5	38921.9	39735.4
35	20.3	2.38	932.1523	259.1	126.1	720.3	400.1	1223.4	47054.9	48278.3
40	25.3	2.72	926.4728	267.1	130.1	728.3	404.6	1645.7	54111.7	55757.4
45	30.3	3.06	921.3343	274.2	134.5	735.4	408.5	2112.9	60158.1	62271.0
50	35.3	3.40	916.6316	280.8	138.2	742.0	412.2	2550.4	65613.8	68164.2
55	40.3	3.74	912.2906	286.8	141.5	748.0	415.5	2999.9	70428.7	73428.6
60	45.3	4.08	908.2472	292.5	144.7	753.7	418.7	3449.2	74884.6	78333.8
65	50.3	4.42	904.4621	297.7	147.6	758.9	421.6	3899.8	78850.5	82750.3
70	55 3	4.76	900.8991	302.7	150.4	753.9	424.4	4361.1	82577.7	86938.8
75	60.3	5.10	897.5269	307.3	152.9	768.5	426.9	4815.8	85923.6	90739.4
80	65.3	5.44	894.3304	311.8	155.4	773.0	429.4	5206.5	89138.7	94345.2
85	70.3	5.78	891.2862	316.0	157.7	777.2	431.7	5638.9	92073.3	97712.2
90	75.3	6.12	888.3758	320.0	160.0	781.2	434.0	6058.1	94814.7	100872.8
95	80.3	6.46	885.5887	323.8	162.1	785.0	436.1	6474.2	97447.2	103921.4
100	85.3	6.80	882.9144	327.5	164.1	788.7	438.1	6885.2	99787.6	106672.8
105	90.3	7.14	880.3429	331.1	166.1	792.3	440.1	7290.3	102163.3	109453.6
110	95.3	7.48	877.8653	334.5	168.0	795.7	442.0	7689 0	104334.9	112023.9
115	100.3	7.82	875.4721	337.8	169.8	799.0	443.8	8087.3	106421.7	114509.0
120	105.3	8.16	873.1555	340.9	171.6	802.1	445.6	8483.1	108325.4	116808.5
125	110.3	8.50	870.9115	344.0	173.3	805.2	447.3	8864.9	110219.9	119084.8
130	115.3	8.84	868.7351	347.0	175.0	808.2	449.0	9252.6	112025.6	121278.2

TOTAL AVAILABLE ENERGY IN WATER AND STEAM.—CONTINUED.

135	120.3	9.18	866.6223	349.9	176.6	811.1	450.6	9627.0	113745.7	123372.7
140	125.3	9.52	864.5661	352.7	178.1	813.9	452.1	9992.6	115382.1	125374.7
145	130.3	9.86	865.5679	355.5	179.7	816.7	453.7	10361.0	117003.5	127364.5
150	135.3	10.20	860.6213	358.1	181.1	819.3	455.1	10536.5	118477.2	129003.7
155	140.3	10.54	858.7276	360.7	182.6	821.9	456.6	11085.9	119939.4	131025.3
160	145.3	10.88	958.8740	363.2	184.0	824 4	458.0	11444.2	121323.6	132767.8
165	150.3	11.22	855.0654	365.7	185.4	826.9	459.4	11823.4	122697.8	134521.2
170	155.3	11.56	853.2942	368.1	186.7	829.3	460.7	12141.3	123995.5	136136.8
175	160.3	11.90	851.5670	370.5	188.0	831.7	462.0	12508.7	125284 7	137793.4
180	165.5	12.24	849.8698	372.8	189.3	834.0	463.3	12821.4	126499.1	139320.5
185	170.3	12.58	848.2086	375.0	190.5	836.2	464.5	13182.0	127642.4	140824.4
190	175.3	12.92	846.5844	377.2	191.7	838.4	465.7	13367.1	128778.8	142145.9
195	180.3	13.26	844.9938	379.4	193.0	840.6	467.0	13844.1	129908.3	143752.4
200	185.3	13.60	843.4326	381.5	194.1	842.7	468.1	14153.3	130967.4	145120.7
210	195.3	14.28	840.3967	385.6	196.4	846.8	470.4	14830.8	133003.2	147834.0
220	205.3	14.66	838.5864	389.8	198.7	851 0	472.7	15463.1	136003.3	151466.4
230	215.3	15.64	833.9691	394.2	201.2	855.4	475.2	16180.3	137134.2	153314.7
240	225.3	16.32	832.6419	397.9	203.3	859.1	477.3	16790.2	139094.3	155884.5
250	235.3	17.00	830.3630	401.0	205.0	862.2	479 0	17314.4	140516.0	157830.4
500	485.3	34.01	780.8592	467.6	242.0	898.8	516.0	30055.5	165892.7	195948.2
1000	985.3	68.02	720.4350	546.8	286.0	1008.0	560.0	48671.5	179212.0	227883.5
2000	1985.3	136.05	643.9049	643.7	339.8	1104.9	613.8	75777.2	194221.3	269998.5
3000	2985 3	204.08	590.8038	708.3	375.7	1169.5	649.7	96116.3	193555.0	289671.3
4000	3985.3	272.10	544.6774	763.7	405.9	1223.9	679.9	114498.6	189201.7	303700.3
5000	4985.3	340.13	505.7339	807.8	431.0	1269.0	705.1	130494.2	183305.9	313800.1
6000	5985.3	408.16	471.8473	845.9	452.1	1307.3	726.1	144413.4	176656.9	321070.3
7000	6985.3	486.19	439.9985	881.2	471.7	1342.4	745.7	157944.2	169333.3	327277.5
8000	7985.3	544.21	409.4533	914.3	490.1	1375.5	764.1	170832.0	161392.6	332224.6
9000	8985.3	612.24	382.6347	945.2	507.3	1406.4	781.5	183998.6	153998.0	337142.6
10000	9985.3	680.27	355.2491	971.4	521.8	1432.6	795.8	193787.0	145376.8	339164.2
100000	99985.3	6802.72	305.3040	2063.4	1184.1	2624.6	1458.1			

4. **The Deductions** from these calculations are of extraordinary importance and interest. Studying the table, the most remarkable fact noted at the lower pressures is the enormous difference in the amounts of energy, in available form, contained in the water and in the steam, and between the energy of sensible heat and that of latent heat, the sum of which constitutes the total energy of the steam. At 20 pounds per square inch above zero (1.36 atmos.), the water contains but 145.9 foot-pounds per pound; while the latent heat is equivalent to 16,872.9 foot-pounds, or more than 115 times as much; *i. e.*, the steam yields 115 times as much energy in the form of latent heat, per pound, as does the water from which it is formed, at the same temperature. The temperature is low; but the amount of energy expended in the production of the molecular change resulting in the conversion of the water into steam is very great, in consequence of the enormous expansion then taking place. At 50 pounds, the ratio is 20 to 1; at 100 pounds per square inch, it is 14 to 1, at 500 it is 5 to 1; while at 5000 pounds the energy of latent heat is but 1.4 that of the sensible heat. The two quantities become equal at 7500 pounds. At the highest temperature and pressure tabled, the same law would make the latent heat negative; it is of course uncertain what is the fact at that point.

At 50 pounds per square inch the energy of heated water is 2550.4 foot-pounds, while that of the steam is 68,184, or enough to raise its own weight to a height in each case of a half-mile or of 12 miles. At 75 pounds

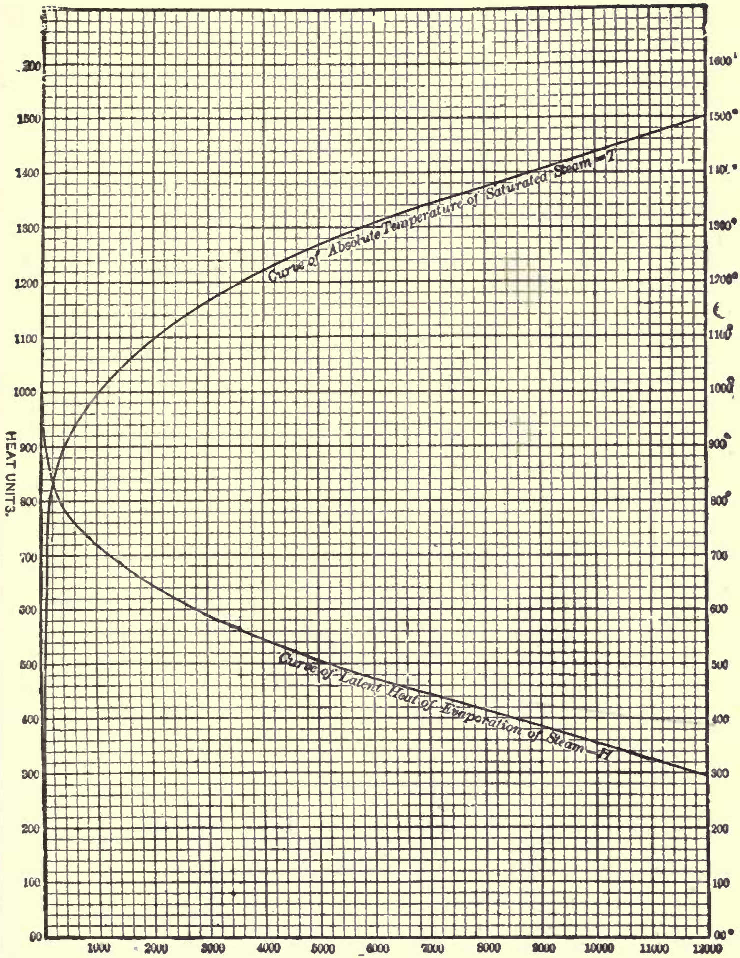

FIG. 1.—CURVE OF HEAT IN STEAM.

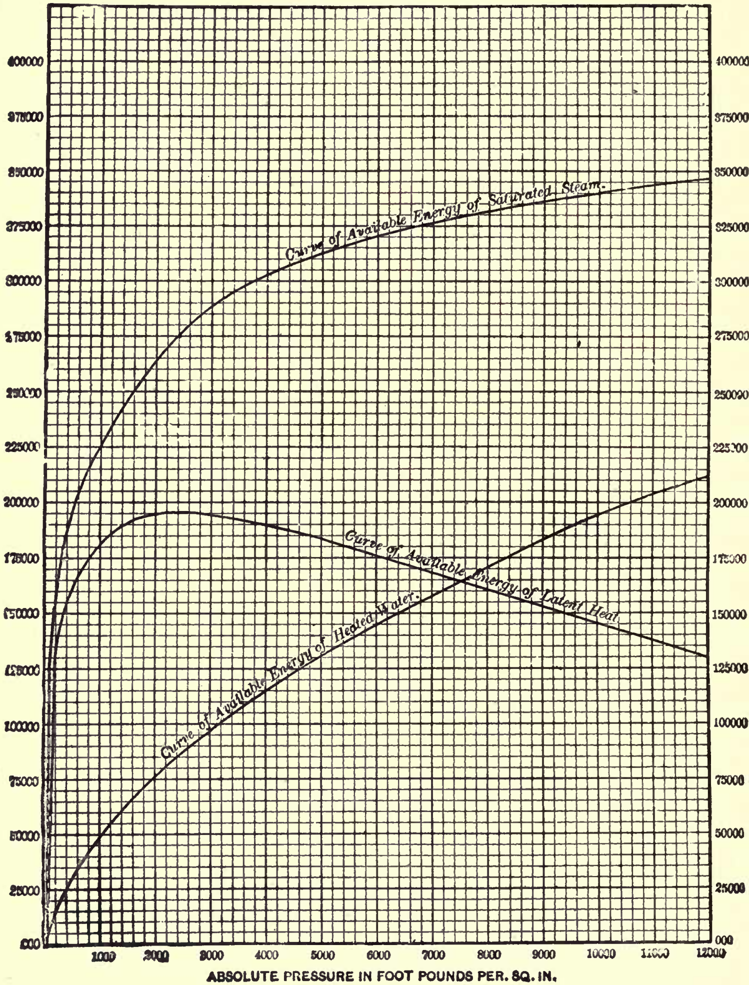

FIG. 2.—CURVE OF HEAT-ENERGY IN STEAM.

the figures are 4816 and 90,739, or equivalent to the work demanded to raise the unit weight to a height of four-fifths, and of about 17 miles, respectively. At 100 pounds the heights are over one mile for the water, and above 20 miles for the steam. The latent heat is not, however, all effective.

5. **The Curve of Energy** obtained by plotting the tabulated figures and determining the form of the curve representing the law of variation of each set, are seen in the peculiar set of diagrams exhibited in the accompanying engravings. In Figure 1 are seen the curves of absolute temperature and of latent heat as varying with variation of pressure. They are smooth and beautifully formed lines, but have no relation to any of the familiar curves of the text books on co-ordinate geometry. In Figure 2 are given the curves of available energy of the water of latent heat, and of steam. The first and third have evident kinship with the two curves given in the preceding illustration; but the curve of energy of latent heat is of an entirely different kind, and is not only peculiar in its variation in radius of curvature, but also in the fact of presenting a maximum ordinate at an early point in its course. This maximum is found at a pressure of about one ton per square inch, a pressure easily attainable by the engineer.

Examining the equations of those curves it is seen that they have no relation to the conic sections, and that the curve, the peculiarities of which are here noted, is symmetrical about one of its abscissas, and that it must have, if the expression holds for such pressures,

another point of contrary flexure at some enormously high pressure and temperature. The formula is not, however, a "rational" one, and it is by no means certain that the curve is of the character indicated; although it is exceedingly probable that it may be. The presence of the characteristic point, should experiment finally confirm the deduction here made, will be likely to prove interesting, and it may be important; its discovery may possibly prove to be useful.

The curve of energy of steam is simply the curve obtained by the superposition of one of the preceding curves upon the other. It rises rapidly at first, with increase of temperature, then gradually rises more slowly, turning gracefully to the right, and finally becoming nearly rectilinear. The curve of available energy of heated water exhibits similar characteristics; but its curvature is more gradual and more uniform. It must be observed, however, that the expression is here employed for pressures far outside the limits of either common experience or direct experiment and hence cannot be checked. It may depart, in an important degree, at its higher ranges from the actual fact.

STEAM BOILER EXPLOSIONS.

6. Steam Boiler Explosions are among the most terrible and disastrous of the many kinds of accidents the introduction of which has marked the advancement of civilization and its material progress.* Introduced by Captain Savery at the beginning of the 18th Century, with the first attempts to apply steam-power to useful purposes, they have increased in frequency and in their destructiveness of life and property continually, with increasing steam-pressures, and the uninterrupted growth of these magazines of stored energy, until, to-day, the amount of available energy so held in control, and liable at times to break loose, is often as much as two, or even three, millions of foot-pounds (276,500 to 414,760 kilogram-meters), and sufficient to raise the enclosing vessel 10,000, or even 20,000 feet (3048 to 6096 m.) into the air, the fluid having a total energy, pound for pound, only comparable with that of gunpowder.

*Portions of this chapter are taken from the notes from which a paper by the Author " On Steam Boilers as Magazines of Explosive Energy " was prepared. See Trans. Am. Society M. E., 1884; and Jour. Frank. Inst., Nov., 1884. Manual of Steam-boilers, Thurston; Chap. XV.

A committee of the British Association, at the session of 1869, reporting on this subject, after remarking that explosions were occurring still, with their accustomed frequency and fatality, go on to say:*

"Sad as it is when those connected with boilers and who gain their livelihood from working them are injured, it is even more so when outsiders who have no interest in their use, or control over their management, are victimized by their explosion, more especially when those victims are women and children. Such, however, is by no means an infrequent occurrence. In one case, a child, asleep in its bed, unconscious of all danger, was killed on the spot by a fragment of an exploded boiler sent through the roof like a thunderbolt. In a second case a young woman working at her needle in an upstairs room, in her own dwelling, was struck by a boiler which was hurled from its seat and dashed against the window at which she sat. The injury was serious—her leg had to be amputated, and death shortly after ensued. In a third case, just as an infant was making its first essay across the kitchen-floor in a collier's cottage, a fragment from an exploded boiler came crashing through the roof, and striking down the child, killed it on the spot. In a fourth case, a woman was standing at her own cottage door with an infant in her arms, when one of the bricks sent flying through the air by the bursting of a boiler struck the little one on the head, and killed it in its mother's arms. In a fifth case, a group of boys were

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*London Engineer, Oct. 8, 1869, p. 237.

sporting in a meadow, when the boiler of a locomotive engine, just drawn up at an adjoining station, burst, and scattering its fragments among the group, killed one of the boys on the spot and injured another." And many more such incidents might be related.

In this and the following article it is proposed to present the results of a series of calculations relating to the magnitude of the available energy contained in masses of steam and of water in steam-boilers. This energy has been seen to be measured by the amount of work which may be obtained by the gradual reduction of the temperature of the mass to that due atmospheric pressure by continuous expansion.

The subject is one which has often attracted the attention of both the man of science and the engineer. Its importance, both from the standpoint of pure science and from that of science applied in engineering and the minor arts, is such as would justify the expenditure of vastly more time and attention than has ever yet been given it. Mr. Airy* and Professor Rankine† published papers on this subject in the same number of the *Philosophical Magazine* (Nov., 1863), the one dated the 3d of September and the other the 5th of October of that year. The former had already presented an abstract of his work at the meeting of the British Association of that year.

In the first of these papers, it is remarked that "very

*Numerical Expression of the Destructive Energy in the Explosions of Steam Boilers.

†"On the Expansive Energy of Heated Water.

little of the destructive effect of an explosion is due to the steam which is confined in the steam-chamber at the moment of the explosion. The rupture of the boiler is due the expansive power common at the moment to the steam and the water, both at a temperature higher than the boiling point; but as soon as the steam escapes, and thereby diminishes the compressive force upon the water, a new issue of steam takes place from the water, reducing its temperature; when this escapes, and further diminishes the compressive force, another issue of steam of lower elastic force from the water takes place, again reducing its temperature; and so on, till at length the temperature of the water is reduced to the atmospheric boiling point, and the pressure of the steam (or rather the excess of steam-pressure over atmospheric pressure) is reduced to 0."

Thus it is shown that it is the enormous quantity of steam so produced from the water, during this continuous but exceedingly rapid operation, that produces the destructive effect of steam-boiler explosions. The action of the steam which may happen to be present in the steam-space at the instant of rupture is considered unimportant.

Mr. Airy had, as early as 1849, endeavored to determine the magnitude of the effect thus capable of being produced, but had been unable to do so in consequence of deficiency of data. His determinations, as published finally, were made at his request by Professor W. H. Miller. The data used are the results of the experiments of Regnault and of Fairbairn and Tate, on the

relations of pressure, volume and temperature of steam, and of an experiment by Mr. George Biddle, by which it was found that a locomotive boiler, at four atmospheres pressure, discharged one-eighth of its liquid contents by the process of continuous evaporization above outlined, when, the fire being removed, the pressure was reduced to that of the atmosphere. The process of calculation assumes the steam so formed to be applied to do work expanding down to the boiling point, in the operation. The work so done is compared with that of exploding gunpowder, and the conclusion finally reached is that "the destructive energy of one cubic foot of water, at a temperature which produces the pressure of 60 lbs. to the square inch, is equal to that of one pound of gunpowder."

The work of Rankine is more exact and more complete, as well as of greater practical utility. The method adopted is that which has been described, and involves the application of the formulas for the transformation of heat into work which had been ten years earlier derived by Rankine and by Clausius, independently. This paper would seem to have been brought out by the suggestion made by Airy at the meeting of the British Association. Rankine shows that the energy developed during this, which is an adiabatic method of expansion, depends solely upon the specific heat and the temperatures at the beginning and the end of the expansion, and has no dependence, in any manner, upon any other physical properties of the liquid. He then shows how the quantity of energy latent in heated

water may be calculated, and gives, in illustration, the amount so determined for eight temperatures exceeding the boiling point. This subject attracted the attention of engineers at a very early date. Familiarity with the destructive effects of steam-boiler explosions, the singular mystery that has been supposed to surround their causes, the frequent calls made upon them, in the course of professional practice and of their studies, to examine the subject and to give advice in matters relating to the use of steam, and many other hardly less controlling circumstances, invest this matter with an extraordinary interest.

A steam-boiler is a vessel in which is confined a mass of water, and of steam, at a high temperature, and at a pressure greatly in excess of that of the surrounding atmosphere. The sudden expansion of this mass from its initial pressure down to that of the external air, occurring against the resistance of its "shell" or other masses of matter, may develop a very great amount of work by the transformation of its heat into mechanical energy, and may cause, as daily occurring accidents remind us, an enormous destruction of life and property. The enclosed fluid consists, in most cases, of a small weight of steam and a great weight of water. In a boiler of a once common and still not uncommon marine type, the Author found the weight of steam to be less than 250 pounds, while the weight of water was nearly 40,000 pounds. As will be seen later, under such conditions, the quantity of energy stored in the water is vastly in excess of that contained in the steam,

notwithstanding the fact that the amount of energy per unit of weight of fluid is enormously the greater in the steam. A pound of steam, at a pressure of six atmospheres (88.2 pounds per square inch), above zero of pressure, and at its normal temperature, 177C. (319°F.), has stored in it about 75 British Thermal Units (32 Calories), or nearly 70,000 foot-pounds of mechanical energy per unit of weight, in excess of that which it contains after expansion to atmospheric pressure. A pound of water accompanying that steam, and at the same pressure, has stored within it about one-tenth as much available energy. Nevertheless, the disproportion of weight of two fluids is so much greater as to make the quantity of energy stored in the steam contained in the boiler quite insignificant in comparison with that contained in the water. These facts are fully illustrated by the figures presented.

7. **The Energy Stored** in steam boilers is capable of very exact computation by the methods already described, and the application of the results there reached gives figures that are quite sufficient to account for the most violently destructive of all recorded cases of explosion.

A steam-boiler is not only an apparatus by means of which the potential energy of chemical affinity is rendered actual and available, but it is also a storage-reservoir, or a magazine, in which a quantity of such energy is temporarily held, and this quantity, always enormous, is directly proportional to the weight of water and of steam which the boiler at the time contains.

Comparing the energy of water and of steam in the steam-boiler with that of gunpowder,as used in ordnance, it has been found that at high pressures the former become possible rivals of the latter. The energy of gunpowder is somewhat variable, but it has been seen that a cubic foot of heated water, under a pressure of 60 or 70 pounds per square inch, has about the same energy as one pound of gunpowder. The gunpowder exploded has energy sufficient to raise its own weight to a height of nearly 50 miles; while the water has enough to raise that weight about one-sixtieth that height. At a low red heat, water has about 40 times this latter amount of energy in a form to be so expended. Steam, at 4 atmospheres pressure, *yields* about one-third the energy of an equal weight of gunpowder. At 7 atmospheres, it gives as much energy as two-fifths of its own weight of powder, and at higher pressures its available energy increases very slowly.

Below are presented the weights of steam and of water contained in each of the more common forms of steam-boilers, the total and relative amounts of energy confined in each under the usual conditions of working in every-day practice, and their relative destructive power in case of explosion.

In illustration of the results of application of the computations which have been given, and for the purpose of obtaining some idea of the amount of destructive energy stored in steam boilers of familiar forms, such as the engineer is constantly called upon to deal with, and such as the public are continually en-

dangered by, the following table has been calculated. This table is made up by Mr. C. A. Carr, U. S. N., from notes of dimensions of boilers designed by, or managed, at various times, by the Author, or in other ways having special interest to him. They include nearly all of the forms in common use, and are representative of familiar and ordinary practice.

No. 1 is the common, simple, plain cylindrical boiler. It is often adopted when the cheapness of fuel or the impurity of the water-supply renders it unadvisable to use the more complex, though more efficient, kinds. It is the cheapest and simplest in form of all the boilers. The boiler here taken was designed by the Author many years ago for a mill so situated as to make this the best form for adoption, and for the reasons above given. It is thirty inches in diameter, thirty feet long, and is rated at ten H. P., although such a boiler is often forced up to double that capacity. The boiler weighs a little over a ton, and contains more than twice its weight of water. The water, at a temperature corresponding to that of steam at 100 pounds pressure per square inch, contains over 46,600,000 foot-pounds of available explosive energy, while the steam, which has but one-fifth of one per cent. of the weight of the water, stores about 700,000 foot-pounds, giving a total of 47,000,000 foot-pounds, nearly, or sufficient to raise one pound nearly 10,000 miles. This is sufficient to throw the boiler 19,000 feet high, or nearly four miles, and with an initial velocity of projection of 1,100 feet per second.

Comparing this with the succeeding cases, it is seen

TOTAL STORED* ENERGY OF STEAM BOILERS.

Type.	Area of G. S.	Area of H. S.	Pressure. Lbs. per Sq. inch.	Rated Power H. P.	Weight of Boiler.	Weight of Water.	Weight of Steam.
	Sq. Feet.				Lbs.		
1 Plain Cylinder	15	120	100	10	2500	5764	11.325
2 Cornish	36	730	30	60	16950	27471	31.45
3 Two-flue Cylinder	20	400	150	35	6775	6840	37.04
4 Plain Tubular	30	851.97	75	60	9500	8255	20.84
5 Locomotive	22	1070	125	525	19400	5260	21.67
6 "	30	1350	125	650	25000	6920	31.19
7 "	20	1200	125	600	20565	6450	25.65
8 "	15	875	125	425	14020	6330	19.02
9 Scotch Marine	32	768	75	300	27045	11765	29.8
10 "	50.5	1119.5	75	350	37972	17730	47.2
11 Flue & Return Tubular	72.5	2324	30	200	56000	42845	69.81
12 "	72	1755	30	180	56000	48570	73.07
13 Water Tube	70	2806	100	250	34450	21325	35.31
14 "	100	3000	100	250	45000	28115	58.5
15 "	100	3000	100	250	54000	13410	21.64

TOTAL STORED ENERGY OF STEAM BOILERS.—*Continued.*

Type.	Stored Energy in (available) Water.	Stored Energy in (available) Steam.	Stored Energy in (available) Total.	Energy per lb. of B'l'r	Energy per lb. of Tot W't	Max. Height of Project'n. B'l'r	Max. Height of Project'n. Tot	Initial Velocity B'l'r	Initial Velocity Tot.
	Foot lbs.			Ft.lbs.		Feet.		Feet per Second.	
1 Plain Cylinder	46,605,200	676,698	47,281,898	18913	5714	18913	5714	1103	606
2 Cornish	57,570,750	709,310	58,260,060	3431	1314	3431	1314	471	290
3 Two-flue Cyl'der	80,572,050	2,377,357	82,949,407	12243	6076	12243	6076	888	625
4 Plain Tubular	50,008,790	1,022,731	51,031,521	5372	2871	5372	2871	588	430
5 Locomotive	52,561,075	1,483,896	54,044,971	2786	2189	2786	2189	423	375
6 "	69,148,790	2,136,802	71,284,592	2851	2231	2851	2231	428	379
7 "	64,452,270	1,766,447	66,218,717	3219	2448	3219	2448	455	397
8 "	64,253,160	1,302,431	65,555,591	4677	3213	4677	3213	549	455
9 Scotch Marine	71,272,370	1,462,430	72,734,800	2689	1873	2689	1873	416	348
10 "	107,408,340	2,316,392	109,724,732	2889	1968	2889	1968	431	356
11 Flue & Ret'n T'blr	90,531,490	1,570,517	92,101,987	1644	931	1644	931	325	245
12 "	102,628,410	1,643,854	104,272,264	1862	996	1862	996	346	253
13 Water Tube	172,455,270	2,108,110	174,563,380	5067	3073	5067	3073	571	445
14 "	227,366,000	3,513,830	230,879,830	5130	3155	5130	3155	575	450
15 "	108,346,670	1,311,377	109,624,283	2030	1626	2030	1626	361	323

* This "stored" energy is less than that available in the non-condensing engine by the amount of the latent heat of external work $(p_1 - p_2)\,v$.

that this is the most destructive form of boiler on the whole list. Its simplicity and its strength of form make it an exceedingly safe boiler, so long as it is kept in good order and properly managed; but, if through phenomenal ignorance or recklessness on the part of proprietor or attendant, the boiler is exploded, the consequences are usually exceptionally disastrous.

No. 2 was a "Cornish" boiler, designed by the Author, about 1860, and set to be fired under the shell. It was 6 feet by 36, and contained a 36-inch flue. The shell and flue were both of iron ⅜-inch in thickness. The boiler was tested up to 60 pounds, at which pressure the flue showed some indications of alteration of form. It was strengthened by stay-rings, and the boiler was worked at 30 pounds. The boiler contained about 12 tons of water, weighed itself 7½ tons, and the volume of steam in its steam space weighed but 31½ pounds. The stored available energies were about 57,600,000 foot-pounds, and about 700,000 of foot-pounds in the water and steam, respectively, a total of nearly 60,000,000. This was sufficient to throw the boiler to the height of 3,400 feet, or over three-fifths of a mile.

Comparing this with the preceding, it is seen that the introduction of the single flue, of half the diameter of the boiler, and the reduced pressure, have reduced the relative destructive power to but little more than one-sixth that of the preceding form.

No. 3 is a "two-flue" or Lancashire boiler, similar in form and in proportions to many in use on the

steamboats plying on our Western rivers, and which have acquired a very unenviable reputation by their occasional display of energy when carelessly handled. That here taken in illustration was designed by the Author, 42 inches in diameter, with two 14-inch flues of 3/8 iron, and is here taken as working at a pressure, as permitted by law, of 150 pounds per square inch. It is rated at 35 horse-power, but such a boiler is often driven far above this figure. The boiler contains about its own weight, 3 tons, of water, and but 37 pounds of steam. The stored available energy is 83,000,000 foot-pounds, of which the steam contains but a little above five per cent. An explosion would uncage sufficient energy to throw the boiler nearly 2½ miles high, with an initial velocity of 900 feet per second. Both this boiler and the plain cylinder are thus seen to have a projectile effect only to be compared to that of ordnance.

No. 4 is the common plain tubular boiler, substantially as designed by the Author at about the same time with those already described. It is a favorite form of boiler, and deservedly so, with all makers and users of boilers. That here taken is 60 inches in diameter, containing 66 3-inch tubes, and is 15 feet long. The specimen here chosen has 850 feet of heating and 30 feet of grate surface, is rated at 60 horse-power, but is often driven up to 75, weighs 9,500 pounds, and contains nearly its own weight of water, but only 21 pounds of steam, when under a pressure of 75 pounds per square inch, which is below its safe allowance. It stores

51,000,000 foot-pounds of energy, of which but 4 per cent. is in the steam, and this is enough to drive the boiler just about one mile into the air, with an initial velocity of nearly 600 feet per second. The common upright tubular boiler may be classed with No. 4.

Nos. 5–8 are locomotive boilers, of which drawings and weights were furnished by the builders. They are of different sizes and for both freight and passenger engines. The powers are probably rated low. They range from 15 to 50 square feet in area of grate, and from 875 to 1350 square feet of heating surface. In weight the range is much less, running from 2½ to a little above 3 tons of water, and from 20 to 30 pounds of steam, assuming all to carry 125 pounds pressure. The boilers are seen to weigh from 2½ to 3 times as much as the water. These proportions differ considerably from those of the stationary boilers which have been already considered. The stored energy averages about 70,000,000 foot-pounds and the heights and velocities of projection not far from 3000 and 500 feet; although, in one case, they became nearly one mile, and 550 feet respectively. The total energy is only exceeded, among the stationary boilers, by the two-flued boiler at 150 pounds pressure.

Nos. 9 and 10 are marine boilers of the Scotch or "drum" form. These boilers have come into use by the usual process of selection, with the gradual increase of steam pressures occurring during the past generation as an accompaniment of the introduction of the compound engine and high ratios of expansion. The

selected examples are designed for use in recent vessels of the U. S. Navy. The dimensions are obtained from the Navy Department, as figured by the Chief Draughtsman, Mr. Geo. B. Whiting. The first is that designed for the "Nipsic," the second for the "Despatch." They are of 300 and 350 horse power, and contain, respectively, 73,000,000 and 110,000,000 of foot-pounds of available energy, or about 3,000 foot-pounds per pound of boiler, and sufficient to give a height and velocity of projection of 3,000 and above 400 feet. These boilers are worked at a lower pressure than locomotive boilers; but the pressure is gradually and constantly increasing from decade to decade, and the amount of explosive energy carried in our modern steam-vessels is thus seen to be already equal to that of our locomotives, and in some cases already considerably exceeds that which they would carry were they supplied with boilers of the locomotive type and worked at locomotive pressures. The explosion of the locomotive boiler endangers comparatively few lives and seldom does serious injury to property, outside the engine itself. The explosion of one of these marine boilers while at sea would be likely to be destructive of many lives, if not of the vessel itself and all on board.

Nos. 11 and 12 are boilers of the old types, such as are still to be seen in steamboats plying upon the Hudson and other of our rivers, and in New York harbor and bay. No. 11 is a return tubular boiler having a shell ten feet in diameter by 23 feet long, 2 furnaces each 7½ feet deep, 5 15-inch and 2 9-inch flues, and 85

return tubes, 4½ inches by 15 feet. The boiler weighs 25 tons, contains nearly 20 tons of water and 70 pounds of steam, and at 30 pounds pressure stores 92,000,000 foot-pounds of available energy, of which 2½ per cent. resides in the steam. This is enough to hoist the boiler one-third of a mile with a velocity of projection of 330 feet per second. The second of these two boilers is of the same weight, also of about 200 horse power, but carries a little more water and steam, and stores 104,000,-000 foot-pounds of energy, or enough to raise it 1,900 feet. This was a return-flue boiler, 33 feet long and having a shell 8¾ feet in diameter, flues 8½ to 15 inches in diameter, according to location.

The "sectional" boilers are here seen to have, for 250 horse-power each, weights ranging from about 35,000 to 55,000 pounds, to contain from 15,000 to 30,000 pounds of water and from 25 to 58 pounds of steam, to store from 110,000,000 to 230,000,000 foot-pounds of energy, equal to from 2,000 to 5,000 foot-pounds per pound of boiler. The stored available energy is thus usually less than that of any of the other stationary boilers, and not very far from the amount stored, pound for pound, by the plain tubular boiler, the best of the older forms. It is evident that their admitted safety from destructive explosion does not come from this relation, however, but from the division of the contents into small portions, and especially from those details of construction which make it tolerably certain that any rupture shall be local. A violent explosion can only come of the general disruption of a

boiler and the liberation at once of large masses of steam and water.

8. The Energy of Steam Alone, as stored in the boiler, is given by column 10 of the preceding table. It has been seen that it forms but a small and unimportant fraction of the total stored energy of the boiler. The next table exhibits the effect of this portion of the total energy, if considered as acting alone.

STORED ENERGY IN THE STEAM SPACE OF BOILERS.

Type.	Energy, Total.	Stored in Steam (ft. lbs.) per lb. of Boiler.	Height of Projection	Initial Velocity. per sec.
1. Plain Cylinder	676,693	271	271 ft.	132 ft.
2. Cornish	709,310	42	42 "	32 "
3. Two-flue Cylinder	2,377,357	351	351 "	150 "
4. Plain tubular	1,022,731	108	108 "	83 "
5. Locomotive	1,483,896	76	76 "	69 "
6. "	2,135,802	85	85 "	74 "
7. "	1,766,447	86	86 "	74 "
8. "	1,302,431	107	107 "	83 "
9. Scotch Marine	1,462,430	54	54 "	59 "
10. " "	2,316,392	61	61 "	62 "
11. Flue and Return Tube	1,570,517	28	28 "	42 "
12. " " "	1,643,854	29	29 "	43 "
13. Water-tube	2,108,110	61	61 "	59 "
14. "	3,513,830	79	79 "	71 "
15. "	1,311,377	24	24 "	39 "

The study of this table is exceedingly interesting, if made with comparison of the figures already given, and with the facts stated above. It is seen that the height of projection, by the action of steam alone, under the most favorable circumstances, is not only small, insignificant indeed, in comparison with the height due the total stored energy of the boiler, but is probably entirely too small to account for the terrific results of ex-

plosions frequently taking place. The figures are those for the stored energy of steam in the working boiler; they may be doubled, or even trebled, for cases of low water; they still remain, however, comparatively insignificant.

The enormous force of molecular power, even when heat is not added to reinforce them, is illustrated by the often described experiments of an artillery officer at Quebec* and others, in which a large bombshell is filled

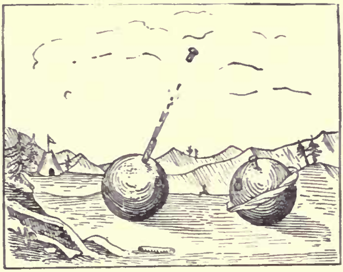

FIG. 3. EXPANSIVE FORCE OF ICE.

with water, tightly plugged, and exposed to low temperatures. In such cases the expansive force exerted, when freezing, by the formation of ice and the increase of volume accompanying the formation of the crystals, either drives out the plug, sometimes projecting it hundreds of yards (Fig. 3), or actually bursts the thick iron case.

In the more familiar cases of purposely produced explosion, the expansion is caused by the production of great quantities of gas previously in solid form. The

* Phenomena of Hunt: Cazin.

violence of the familiar explosives as used in ordnance, in mining operations, is commonly due to this combined effect of heat and chemical action, occurring by the sudden action of powerful forces. In the steam-boiler explosion, mighty forces previously long held in subjection, finally overcome all resistance, and their sudden application to external bodies constitute the disaster.

9. **Explosion and Bursting** are terms which, as often technically used by the engineer, represent radically different phenomena. The explosion of a steam-boiler is sudden and violent disruption, permitting the stored heat-energy of the enclosed water and steam to be expended in the enormously rapid expansion of its own mass, and, often, in the projection of parts of the boiler in various directions with such tremendous power as to cause as great destruction of life and property as if the explosion were that of a powder-magazine. The

FIG. 4.—AN EXPLOSION.

bursting of a boiler is commonly taken to be the rupture, locally, of the structure, by the yielding of its weakest part to a pressure which, at the moment, may not be deemed excessive, but which is too great for the weakened spot. The collapse of a flue is a form of rupture which is ordinarily considered as of the second class. With high steam-pressure, the bursting, or the collapse, of a flue, may occur with a loud report, and may even cause some displacement of the boiler; but it is not generally termed an explosion where the boiler is simply upturned and is not torn into separated pieces. There is, however, no real boundary, and the one grades into the other, with no defined line of demarkation.

It occasionally happens that an explosion takes place with such extraordinary violence and destructive effect that it has been thought best, especially by French writers, to class it by itself, and it is denoted a detonant or fulminant explosion, "*explosion fulminante.*" In such cases, the report is like that of an enormous piece of ordnance; the boiler is often rent into many parts, or even completely broken up as if by dynamite; and surrounding objects are destroyed as if by the discharge of a park of artillery.

In any steam-boiler, there may, at any time, exist a state of equilibrium between the resisting power of the boiler and the steam-pressure. In ordinary working, the latter is far within the former, but as time passes, the limiting eondition is gradually approached, and, in every explosion, the line is passed. The pressure may

rise until the limit of strength is attained; or the resisting power of the boiler may decrease to the limit; in either case, the passage of the line is marked by explosion or a less serious method of yielding.

10. The Causes of Boiler Explosions are numerous, but are usually perfectly well understood. Where uncertainty exists, it is probably the fact that, were the cause ascertained, it would be found to be simple and well known. It is, nevertheless, true that some authorities, including a few experienced and distinguished members of the engineering profession, believe that there are causes, at once obscure and of great potency and energy, which are not yet satisfactorily understood. In this work, the many causes to which explosions are, by various practitioners and writers, attributed, may be divided into the known, the probable, the possible, the improbable, and the impossible and absurd.

To the first class belong the general and fairly uniform weakness of boilers as compared with the steam-pressure carried; the sticking of safety valves, and the thousand and one other causes having their origin in the ignorance, the carelessness, or the utter recklessness of the designer, the builder, or the attendants entrusted with their management. To this class may be assigned the causes of by far the greater proportion of all explosions; and the Author has sometimes questioned whether this category may not cover absolutely all such catastrophes. To the second class may be assigned "low water," a cause to which it was once customary to attribute nearly all explosions, but which is known to be

seldom operative, and so seldom that some authorities now question the possibility of its action at all.* Among the possible causes, acting rarely and under peculiar conditions, the Author would place the overheating of water, and the storage of energy in excess of that in the liquid at the temperature due the existing pressure; the too sudden opening of the throttle-valve, or the safety-valve, producing priming and shock; the spheroidal state of water; and perhaps other phenomena. The improbable include the latter, however. The action of electricity, a favorite idea with the uninformed, may be taken as an example of the impossible and absurd. The actual causes of a vast majority of boiler explosions are now determined by skilled engineers, inspectors and insurance experts; and it is by them generally supposed that no so-called "mysterious" causes exist, in the sense that they are phenomena beyond the present range of human knowledge and scientific investigation.

All recent authorities agree in attributing boiler-explosions, almost without exception, to one or another of the following general classes of causes, and the Author is inclined to make no exception:

(1.) Defective design: resulting in weakness of shell, of flues, or of bracing or staying; in defective circulation; faulty arrangement of parts; inefficiency of provision for supplying water or taking off steam; and defects in arrangement leading to strains by unequal ex-

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* See opinion of Mr. J. M. Allen, Sibley College Lecture, Sci. Am. Supplement, Feb. 19, 1887, p. 9272.

pansion, and other matters over which the designer had control.

(2.) Malconstruction: including choice of defective or improper material; faulty workmanship; failure to follow instructions and drawings; omissions of stays or braces.

(3.) Decay of the structure with time or in consequence of lack of care in its preservation; local defects due to the same cause or to some unobserved, or concealed leakage while in operation.

(4.) Mismanagement in operation, giving rise to excessive pressure; low water; or the sudden throwing of feed-water on overheated surfaces; or the production of other dangerous conditions; or failure to make sufficiently frequent inspection and test, and thus to keep watch of those defects which grow dangerous with time.

Weakness of boiler or over-pressure of steam are the usual immediate causes of explosions.

It has often been suggested that the most destructive boiler-explosions may be attributable to electricity and may illustrate the effect of an unfamiliar form of lightning. Such hypotheses are, however, absurd. No storage and concentration of electricity could be produced in a vessel composed of the best of conducting materials and inclosing a mass of fluid incapable of causing electrical currents, either great or small, under the conditions observed in the steam-boiler. The production of electricity, seen in Armstrong's experiments, a phenomenon sometimes thought to support this theory, is

simply the result of the friction of a moving jet of steam on the nozzle from which it issued, and presents not the slightest reason for supposing that the electrical hypothesis of the origin of boiler-explosions have any basis of fact.

Professor Faraday, in a report to the British Board of Trade, May, 1859, states his belief in the absurdity of the idea that the water within a steam-boiler may become decomposed and the explosion of a mixture of gasses so produced may burst a boiler. * * * * "As respects the decomposition of the steam by the heated iron, and the separation of hydrogen, no new danger is incurred. Under extreme circumstances, the hydrogen which could be evolved would be very small in quantity, would not exert greater expansive force than the steam, and would not be able to burn with explosion, and probably not at all if it met the steam, escaping through an aperture into the air, or even into the fireplace."

Decomposition cannot occur in the steam-boiler, ordinarily, and if it were to happen in consequence of low water and overheated plates, no oxygen could remain free to explosively combine with it.

A half century ago, M. Arago, in writing of steam boiler explosions,* asserted "that no cause of explosion exists which cannot be avoided by means at once simple and within reach of every one." A committee of the Franklin Institute, in 1830, asserted† of boiler-explo-

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* Mem. Roy. Acad. Sci., Inst. France ; **xxi.**

† Journal Franklin Institute, 1830.

sions that "they proceed, in most cases, from defective machinery, improper arrangement or distribution of parts, or finally, from carelessness in management." These conclusions are fully justified by all later experience, and it is now admitted by all accepted authorities that a careful examination and study of the facts of the case will almost invariably enable the experienced engineer to determine the origin of the disaster. It follows that it is perfectly practicable to so design, construct, and manage steam-boilers that there shall be absolutely no danger of explosion.

That the great majority, if not all, explosions are due to preventible causes was thus very early recognized. President Andrew Jackson, in his fifth Annual Message to Congress, Dec. 3d, 1883, says:

"The many distressing accidents which have of late occurred in that portion of our navigation carried on by the use of steam-power, deserves the immediate and unremitting attention of the constituted authorities of the country. The fact that the number of those fatal disasters is constantly increasing, notwithstanding the great improvements which are everywhere made in the machinery employed, and the rapid advances which have been made in that branch of science, show very clearly that they are in a great degree the result of criminal negligence on the part of those to whose care and attention the lives and property of our citizens are so extensively entrusted.

"That these evils may be greatly lessened, if not substantially removed, by means of precautionary and penal

legislation, seems to be highly probable; so far, therefore, as the subject can be regarded as within the constitutional purview of Congress, I earnestly recommend it to your prompt and serious attention."

Modern experience and recent investigation confirm these statements.

The United Society of Boiler-makers express the general opinion of engineers on this subject in the following language: *

"If masters who manufacture boilers and those who use them would be more judicious in their selection of boilers made of the best materials and after the most approved principles, we should rarely listen to the horrifying details of boiler explosions."

There are, nevertheless, certain defects inherent in the type which involve some risks notwithstanding the facts that good design, good construction, and competent management may minimize them. Such are the risks involved in stayed surfaces such as are often illustrated in locomotive fire-boxes, the liability of the seam of the shell-boiler to crack along the rivet-line under the lap, out of reach of inspection, the cracking of the tubes in water-tube boilers, etc.

In common practice, to-day, however, the specifications are usually so explicit and so detailed that only good materials will be employed, well-settled forms and proportions will be adopted, and construction will be satisfactory. For compliance with specifications the inspector for the purchaser must be responsible.

11. **The Statistics of Explosions** have been very

* London Engineer, July 29, 1870, p. 77.

carefully collected for many years in some European communities, notably in France, and are now given for the United States in very reliable form by inspectors, governmental and private, who are thoroughly familiar with the subject. The following is a list reported for the year 1885 :

CLASSIFIED LIST OF BOILER EXPLOSIONS.

	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Total per Class.
Saw-mills and wood-working shops	5	2	4	3	3	2	2	2	3	4	1	2	33
Locomotives	..	4	..	..	..	1	..	..	1	2	1	1	10
Steamboats, tugs, etc	2	..	2	..	1	1	1	..	..	3	2	4	16
Portables, hoisters and agricultural engines	..	..	..	..	1	2	4	2	3	..	2	2	16
Mines, oil wells, collieries, etc	2	5	3	2	1	1	..	3	..	1	1	1	20
Paper-mills, bleachers, digesters, etc	1	..	..		..	..	1	1	..	..	..	..	3
Rolling-mills and iron-works	1	2	1	..	..	1	1	1	..	1	..	2	10
Distilleries, breweries, sugar-houses, dye-houses, rendering establishments, etc	3	1	..	..	3	1	1	..	3	..	4	2	18
Flour-mills and elevators	..	3	1	..	..	2	..	..	1	..	2	1	10
Textile manufactories	..	..	..	..	..	1	..	..	..	..	..	..	1
Miscellaneous	..	3	3	2	2	1	..	..	..	3	2	2	18
Total per month	14	20	14	7	12	12	10	9	11	14	15	17	155
Persons killed, total **220** per month	24	22	20	9	18	14	7	11	11	19	34	31	...
Persons injured, total **288** per month	35	30	28	9	32	6	21	21	13	40	22	21	...

Boilers used in saw-mills are most frequently exploded, presumably because of the cheapness of their construction, and the unskillfulness exhibited in their management; boilers in mines are next in number of casualities. Factory-boilers explode with comparative infrequency. In the United States, according to the best

estimates which the Author has been able to make, about one boiler in 10,000 explodes among those which are regularly inspected and insured, and ten times that proportion among uninspected and uninsured boilers. According to Reiche,* in Great Britain, recently, one explosion has occurred in every 500 boilers not under inspection; in Prussia, one in 1,000 under state control and inspection; and in Great Britain one in 10,000 boilers in charge of the private inspection companies. Explosions might become almost unknown were a proper system of inspection and compulsory repair introduced.

In Great Britain the proportion of explosions is much less than in the United States, the average number being less than one-twentieth of one per cent., and the loss of life about three to every two explosions. In Great Britain, as in the United States and elsewhere, the majority of explosions are due to negligence.

The returns of boiler-explosions in Great Britain and the United States show that not only in number but in destructiveness the record of the United States always exceeds that of Great Britain, as is seen in the following table.

	No. Explosions.		No. Fatalities.		No. Persons inj'd.	
	1884.	1885.	1884.	1885.	1884.	1885.
Great Britain.........	36	43	24	40	49	62
United States.........	152	155	254	220	261	288

* Anlage und Betrieb der Dampfkessel; H. v. Reiche; Leipzig, 1876.

	No. Explosions per Million Inhabitants.		No. Fatalities per Explosion.	
	1884.	1885.	1884.	1885
Great Britain	1	1.17	.67	.93
United States...... ..	3	3.09	1.67	1.42

The causes of the 43 explosions in Great Britain are reported to have been:

	Cases.
Deterioration or corrosion of boilers and safety-valves............	20
Defective design or construction of boiler or fittings............	11
Shortness of water..	4
Ignorance or neglect of attendants.........................	4
Miscellaneous..	4
Total..	**43**

For the United States there are estimated to have been dangerous cases, classified thus:

Causes.	Whole No.	Dangerous
Deterioration or corrosion of boilers and safety-valves	17,873	1,727
Defective design or construction of boiler or fittings	15,895	2,957
Shortness of water..........................	130	56
Ignorance or neglect of attendants..........	6,404	983
Miscellaneous............................	6,928	1,403

The following are two classified lists of defects and causes of dangerous conditions, where, in one case, over 6,000 boilers, and in the other about 10,000, are inspected : *

Nature of Defects.	Whole Number.	Dangerous.
Deposit of sediment	458	32
Incrustation and scale	630	55
Internal grooving	20	7
Internal corrosion	155	16
External corrosion	346	23
Broken, loose, and defective braces and stays.	205	39
Defective settings	178	17
Furnaces out of shape	248	12
Fractured plates	123	65
Burned plates	89	22
Blistered plates	254	11
Cases of defective riveting	1,649	187
Defective heads	30	15
Leakage around tube ends	974	331
Leakage at seams	574	22
Defective water guages	163	27
Defective blow-offs	30	8
Cases of deficiency of water	5	2
Safety-valves overloaded	29	7
Safety-valves defective in construction	42	7
Defective pressure-guages	238	19
Boilers without pressure-guages	4	0
Defective hand-hole plates	3	3
Defective hangers	13	0
Defective fusible plugs	1	0
Total	6,453	927

* "**The Locomotive,**" Dec., 1884 ; Feb., 1902.

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Nature of Defects.	Whole Number.	Dangerous.
Cases of deposit of sediment	14,109	731
Cases of incrustation and scale	36,137	986
Cases of internal grooving	2,284	153
Cases of internal corrosion	10.383	461
Cases of external corrosion	8,135	532
Defective braces and stays	3,035	680
Settings defective	4,986	363
Furnaces out of shape	5,512	249
Fractured plates	3,802	632
Burned plates	4,691	477
Blistered plates	1,379	39
Defective rivets	32,303	897
Defective heads	998	147
Leakage around tubes	31,925	3,171
Leakage at seams	5,306	308
Water-gauges defective	3,398	626
Blow-offs defective	2,465	702
Cases of deficiency of water	393	123
Safety-valves overloaded	1,180	438
Safety-valves defective	932	323
Pressure-gauges defective	5,284	361
Boilers without pressure gauges	163	163
Unclassified defects	9,047	52
Totals	187,847	12,614

It is seen that many of these defects, all of which are dangerous and liable to cause explosion, are of very variable frequency, as, for example, defective riveting, which is more than twice as common, in the first list, as any other defect, but which stands number three in the second; while other defects are of quite regular occurrence, as the presence of sediment and of scale, grooving, and other corrosion, injured plates and defective guages. Sediment, oxidation, and defective workmanship are evidently the most prolific causes of danger; and unequal expansion, to which many of the reported cases of leakage are attributable, hardly less so.

An inspection of these tables plainly shows that the causes of steam-boiler explosions are commonly perfectly simple and are well understood; and a person familiar with the subject usually wonders that explosions occur as infrequently as they do, where there are so many sources of danger and where so little intelligence and care is exhibited in their design, construction, and operation. There are, however, some interesting phenomena, and some very ingenious theories as to method of liberation of the enormous stock of energy of which every boiler is a reservoir, to which attention may well be given.

12. **Theories and Methods** of explosions due to other causes than simple increase of steam-pressure or decrease in strength of boiler, and of such accidents as are common and well understood, and produce the greater number of disasters of the class here studied, are as various as they are interesting. The vast majority of all boiler-explosions have been, as has been seen, found to be due to causes which are readily detected and are the simplest and most obvious possible. Here and there, however, an explosion takes place which is so exceptionally violent, or which occurs under such unusual and singular conditions, as to give rise to question whether some peculiar phenomenon is not concerned in bringing about so extraordinary a result. Nearly all explosions have been produced either by a gradual rise in pressure until the resisting power of the boiler has been exceeded and an extended rupture liberates the stored energy; or by a gradual reduction

of the strength of the structure until, at last, it is insufficient to withstand the ordinary working pressure, and a general yielding leads to the same result. Such cases require little comment and no explanation. But the rare instances in which a sudden development of forces far in excess of those exhibited in regular working have been believed to have been observed, have given rise to much speculation, to many ingenious theories, and to an immense amount of speculation and misconception on the part of those who are unfamiliar with science and without experience in the operation of this class of apparatus.

Explosions probably always occur from perfectly simple and easily comprehended causes, are always the result of either ignorance or carelessness, and are always preventible where intelligence and conscientiousness govern the design, the construction, and the management of the boiler. A well-designed boiler, properly proportioned for its work and to carry the working pressure, well built, of good materials, and intelligently and carefully handled, has probably never been known to explode. Explosions probably rarely occur, with either a gradually increasing pressure of steam, or decreasing strength of boiler unless the strength of the structure is quite uniform; local weakness is a safety-valve which permits a "burst" and insures against that more general disruption which is called an "explosion." A long line of weakened seam, an extended crack, or a considerable area of surface thinned by corrosion may lead to an explosion and a general breaking up of the

whole apparatus; but any minor defect, when its site is surrounded by strong parts, will not be likely to produce that result.

The Method of Explosion is, in the great majority of cases, the opening of a small orifice at a point of minimum strength, with outrush of water or steam, or both, the rapid extending of the rupture until it becomes so great and the operation so rapid that, no time being given for the gradual discharge of the enclosed fluids, the boiler is torn violently apart by the internal unrelieved pressure and distributed in pieces, the number of which is determined by the character and extent of the lines or areas of weakness. The violence of the projection of the detached parts depends on the magnitude of the pressure and the rapidity with which disruption takes place. The most destructive explosions are often distinguished by a general breaking up of the whole structure. In the case of the "burst" boiler, the opening is of limited extent and the contents of the boiler are discharged without tearing it in pieces.

"Colburn's Theory," to be presently described, is an attempt to state the method of explosion and the reasons therefor, and the other theories, accepted or otherwise, usually attempt the same thing for general or special cases.

13. **Clark and Colburn's Theory** of boiler-explosions has been accepted as a "working hypothesis" by many engineers and has some apparent foundation in experimentally ascertained fact. This theory is attri-

buted to Mr. Zerah Colburn,* but was probably, as stated by Mr. Colburn himself, original with Mr. D. K. Clark, who suggests that a rupture initiated at the weakest part of a boiler, above or near the water-line, may be extended and an explosion precipitated by the impact of a mass of water carried toward it by the sudden outrush of a quantity of steam, precisely as the "water-hammer" observed so frequently in steam-pipes causes an occasional rupture of even a sound and strong pipe. In fact, many instances have been observed in which the rent thus presumed to have been produced has extended not only along lines of reduced section, but through solid iron of full thickness and of the best quality. It is thus that Mr. Clark would account for the shattering and the deformation of portions of the disrupted boiler which are often the most striking and remarkable phenomena seen in such instances.

Colburn suggests that the explosion, in such cases, although seemingly instantaneous, may actually be a succession of operations, three or four, at least, as the following:

(1.) The initial rupture under a pressure which may be, and probably often is, the regular working pressure; or it may be an accidentally produced higher pressure; the break taking place in or so near the steam-space that an immediate and extremely rapid discharge of steam and water may occur.

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*Steam Boiler Explosions: Zerah Colburn. London: John Weale 1860.

(2.) A consequent reduction of pressure in the boiler, and so rapid that it may become considerable before the inertia of the mass of water will permit its movement.

(3.) The sudden formation of steam in great quantity within the water and the precipitation of heavy masses of water, with this steam, toward the opening, impinging upon adjacent parts of the boiler and breaking it open, causing large openings or extended rents, and, often, shattering the whole structure into numerous pieces.

(4.) The completion of the vaporization of the now liberated mass of water to such extent as the reduction of the temperature may permit, and the expansion of the steam so formed, projecting the detached parts to distance depending on the extent and velocity of this action.

This series of phenomena may evidently be the accompaniment of any explosion, to whatever cause the initial rupture may be due. One circumstance lending probability to this theory is the rarity of explosions originating in the failure of "water-legs" or other parts situated far below the water-line. This occasionally happens, as was seen some time ago at Pittsburgh, in the explosion of a vertical boiler, caused by a crack in the water-leg; but it is almost invariably observed that explosions occur where long lines of weakened metal, defective seams, or of "grooving" extend nearly or

quite to the steam space.* A local defect well below the water-line would usually simply act as a safety-valve, discharging the contents of the boiler without explosion.

14. **Corroboratory Evidence** has been here and there found. Lawson's experiments, and those of others, as well as many accidental explosions, have supplied evidence somewhat, but not absolutely, corroboratory of the Clark and Colburn theory. Mr. D. T. Lawson, having become convinced of the truth of the Clark and Colburn theory, further conceived the idea that the opening and sudden closing of the throttle or the safety-valve might cause precisely the same succession of phenomena, and lead to the explosion of boilers; the opening starting the current, and the closing of the valve producing impact that may disrupt the boiler. To test the truth of his hypothesis, he made a number of experiments, and succeeded in exploding a new and strong boiler at a pressure far below that which it had immediately before safely borne. As a preventive, he proposed the introduction of a perforated sheet-iron diaphragm, dividing the interior of the boiler at or near the water-line, the expectation being that it would check the action described by Colburn and prevent that percussive effect to which explosion was attributed by him, and also that it would be found to possess some other advantages.

The experiments were made at Munhall, near Pitts-

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* The "Westfield" explosion illustrates this case. Jour. Frank. Inst., 1875.

burgh, Pa., in March, 1882, the boiler being of the cylindrical variety, 30 inches (76 cm.) in diameter and 7¾ feet (2.06 m.) in length, of iron 3-16 inch (0.48 cm.) in thickness. Its strength was estimated at 430 pounds per square inch (28⅔ atmos.) It was fitted with a diaphragm, as above described.

After some preliminary tests, the following were made,* the valve being opened at intervals and suddenly closed again at the pressures given below, as taken from the log. A steam-guage was attached to the boiler above and another below the diaphragm. The boiler contained 18 inches of water. Steam was generated slowly, and when the pressure had reached 50 pounds, operating the discharge valve began, with the following results:

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* Report of U. S. Inspectors to the Secretary of the Treasury, Mch. 23d 1882.

Steam pressure at which discharge valve was raised.	Steam-gauge above diaphragm.		Steam-gauge below the diaphragm.	
	Needle fell below.	Needle rose above.	Needle fell below.	Needle rose above
Lbs.	Lbs.	Lbs.	Lbs.	Lbs.
50	7	3	3	00
80	10	7	4	00
100	12	7	5	3
125	15	15	8	4
150	20	20	8	7
175	15	23	10	10
200	20	20	15	00
225	30	20	12	00
230	40	30	10	00
250	25	20	10	00
275	30	25	15	00
300	40	35	15	00

When the pressure in the boiler reached 300 pounds to the square inch, it was decided that the boiler had been sufficiently tested, and the boiler was emptied and inspected. The rivets, seams, and all the other parts of the boiler were examined, and no strain, rupture, or weakness was discovered. The diaphragm was then cut out, leaving the flanges riveted to the sides of the shell and across the heads. The boiler was then again tested, with the following results:

Steam pressure at which discharge valve was raised.	Steam-guage attached to the boiler in the steam-space.		Steam-guage attached to the boiler in water-space.	
	Needle fell below.	Needle rose above.	Needle fell below.	Needle rose above.
Lbs.	Lbs.	Lbs.	Lbs.	Lbs.
100	3	00	3	00
125	2	00	3	00
150	5	00	5	00
175	4	2	3	2
200	5	00	5	00
210	3	00	3	00
225	5	00	3	00
235	Exploded.			

When the discharge-valve was opened at 235 pounds pressure, it caused the explosion of the boiler; it was blown into fragments. The iron was torn and twisted into every conceivable shape; strips of various sizes and proportions were found in all directions. The boiler did not always tear at the seams, but principally in the solid parts of the iron.

At the time of the explosion the water-line was higher than during the test immediately preceding. At an earlier privately made experiment, as reported by the same investigator, an explosion of a new boiler had been similarly produced at one-half the pressure which it had been estimated that the boiler might sustain. A significant fact exhibited in the record is the enormously greater fluctuation of pressure in the boiler

during the first than during the second trial, and the difference in the amount of that fluctuation above and below the diaphragm.

The result of this action in the ordinary operation of the safety-valve or of the throttle-valve is apparently extremely uncertain. Many explosions have occurred under such circumstances as would seem to indicate the probability of the action described having been their cause, the disaster following the opening of safety-valve, or of the throttle at starting the engines.

On the other hand, these operations are of constant occurrence and with weak and dangerous boilers, and such explosions are, nevertheless, extremely rare. The Author, while officially engaged in attempting the experimental production of boiler-explosions, as a member of the U. S. Board appointed for that purpose, made numerous experiments of this nature, but never succeeded in producing an explosion. The danger would seem to be, fortunately, less than it might be, judging from the above. The introduction of feed-water into the steam-space of boilers, producing sudden removal of pressure from the surface of the water is sometimes supposed to have caused explosions. The explosion of a battery of several boilers simultaneously—not an infrequent case—is supposed to be attributable to the action described above, following the rupture of some one of the set.

Mr. J. G. Heaffman, writing in 1867,* anticipated Mr. Lawson's idea, and, after describing an explosion of

* Journal of Assoc. of German Engineers, 1867 ; Iron Age, 1867.

a bleaching boiler, to which the steam was supplied from a separate steam-boiler, attributed the catastrophe to impact of water against the shell, or the accidental production of an opening at the manhole, and asserts that explosions thus occur not only from excess of pressure, but also from shock. He further states that, in accordance with a request made by the Association of German Engineers, a commission of the Breslau Association experimenting with a small glass boiler, found that when the escape-pipes are only gradually opened, and the steam allowed gradually to escape, the generation of steam quietly continues and the water remains tranquil. But if the valve is quickly opened, steam bubbles suddenly form all through the water, and rising to the surface, produce violent commotion. In one of these experiments it was his duty to watch the manometer, while another person quickly opened the valve to allow the steam to escape. As soon as the valve was opened the pressure fell 3 lbs., but immediately again began to rise and the boiler exploded. Where it had been in contact with the water it was shattered to powder, which lay around like fine sand. Of the entire boiler only a few small pieces of the size of a dollar were left. Afterward they constructed a similar glass boiler with a cylinder 7 inches in diameter, and 9 inches in length, and to the ends metal heads were fastened; in the heads were pipes for leading in the steam. By means of a force pump the boiler was filled with boiling water, the valve being left open meanwhile, in order that its sides might become evenly

heated. Then half the water was drawn off and air let in, and afterward more boiling water forced in, so that the air was compressed, until the boiler exploded at a pressure of 15 atmospheres.

The report was not nearly as loud as at the former explosion, which took place at a pressure of only 3 atmospheres, and the glass was only broken into several pieces. This, Mr. Heaffman considers, proves that the action of the water on the boiler is such as would be produced by exploding nitro-glycerine in the water.

He goes on to state that, in bleacheries, dye works, etc., the habit often prevails of suddenly opening the steam-cocks, thus endangering the boiler. He does not assert that every time a cock is suddenly opened an explosion *must* follow; but that it *may* take place experience has shown. In the experiments above described they had many times opened the glass boiler without causing an explosion; with the second boiler, too, they had done so without being able to bring about explosion; both with high and low pressure. In the former class of explosions, the steam shatters, twists and contorts the parts in an instant.

"*Water-hammer*" has, by the bursting of steam-pipes, by a process somewhat closely related to that described by Clark and Colburn, sometimes caused fatal injury to those near at the instant of the accident. This is a phenomenon which has long been familiar to engineers, and the Author has been cognizant of many illustrations, in his own experience, of its remarkable effects, and has sometimes known of almost as serious

losses of life as from boiler-explosions. It is rarely the cause of serious loss of property.

When a pipe contains steam under pressure, and has introduced into it a body of cold water, or when a cold pipe, containing water, is suddenly filled with steam, the contact of the two fluids, even when the water is in very small quantities, results in a sudden condensation which is accompanied by the impact of the liquid upon the pipe with such violence as often to cause observable, and very heavy, shocks; and, often, a succession of such blows is heard, the intensity of which are the greater as the pipe is heavier and larger, and which may be startling and even very dangerous. It is not known precisely how this action takes place, but the author has suggested the following as a possible outline of this succession of phenomena: *

The steam, at entrance, passes over, or comes in contact with, the surface of the cold water standing in the pipe. Condensation occurs, at first very slowly, but presently more quickly, and then so rapidly that the surface is broken, and condensation is completed with such suddenness that a vacuum is produced. The water adjacent to this vacuum is next projected violently into the vacuous space, and, filling it, strikes on the metal surfaces, and with a blow like that of a solid body, the liquid being as incompressible as a solid. The intensity of the resulting pressure is the greater as the

* Water-hammer in Steam-pipes; Trans. Am. Soc. Mech. Engrs.; vol. iv. p. 404.

distance through which the surface attacked can yield is the less, and enormous pressures are thus attained, causing the leakage of joints, and even the straining, twisting and bursting of pipes. In some cases, the whole of an extensive line or system of pipes, has been observed to writhe and jump about to such extent as to cause well-grounded apprehensions.

The Author once had occasion to test the strength of pipes which had been thus already burst. They were 8 inches in diameter (20.32 cm.) and of a thickness of 3/8 inch (0.95 cm.) and had been, when new, subjected to a pressure of about 20 atmospheres (300 lbs. per square inch). When tested by the Author in their injured condition, they bore from one-third more to nearly four times as high pressures, before the cracks which had been produced were extended. It is, perhaps, not absolutely certain that some of these pieces of pipe may not have been cracked at lower pressures than the above; but it is hardly probable. It seems to the Author very certain that the pressures attained in his tests were approximately those due to the water-hammer, or were lower. The steam-pressure had never exceeded about four atmospheres (60 lbs. per sq. in).

It is evident that it is not safe, in such cases, to calculate simply on a safe strength based on the proposed steam-pressures, but the engineer may find those actually met with enormously in excess of boiler-pressure, and a "factor-of-safety" of 20 may prove too small, it being found as above, that the water-hammer may produce

local pressure approaching, if not exceeding, 70 atmospheres (1000 lbs. per sq. inch).

These facts, now well ascertained and admitted, lend strong confirmation to the Clark and Colburn theory of explosions.

15. **Energy Stored in Heated Metal** is vastly less in amount, with the same range of temperature, than in water. The specific heat of iron is but about one-ninth that of water, and the weight of metal liable to become overheated in any boiler is very small. If the whole crown-sheet of a locomotive boiler were to be heated to a full red-heat, it would only store about as much heat, per degree, as forty pounds (18 kgs.) of water, or not far from 3000 thermal units (756 calories), or 2,316,000 foot-pounds (33,000 kilog-m., nearly), or about three-tenths of the total energy of the fluids concerned in an explosion. It would be sufficient, however, to considerably increase the quantity of steam present in the steam-space; and this increase, if suddenly produced, and too quickly for the prompt action of the safety-valve, might evidently precipitate an explosion, which would be measured in its effects by the total energy present.

It thus becomes at once obvious that the danger from the presence of this stock of excess energy is determined not only by the weight of metal heated and its temperature, but even more by the rate at which that surplus heat is communicated to the water that may be brought in contact with it, by pumping in feed-water, or by any cause producing violent ebullition. It is probable that this cause has sometimes operated to pro-

duce explosions; but oftener, that the loss of strength produced by overheating is the more serious source of danger. It is also evident that the first is the more dangerous, as the pressures are lower, the second with high pressures.

As illustrating a calculation in detail, assume $\left\{\begin{matrix}\text{2.4 square metres}\\ \text{25 square feet}\end{matrix}\right\}$ of crown-sheet, or boiler shell, overheated $\left\{\begin{matrix}\text{556 degrees } C.\\ \text{1,000 degrees } F.\end{matrix}\right\}$ the metal being $\left\{\begin{matrix}\text{0.95 centimeters}\\ \tfrac{3}{8}\text{ inch}\end{matrix}\right\}$ in thickness and its total weight $\left\{\begin{matrix}\text{170 kilogs.}\\ \text{375 pounds.}\end{matrix}\right\}$ Then the product of weight into range of temperature, into specific heat (0.111) is the measure of the heat-energy stored.

$$375 \times 1000 \times 0.111 = 41{,}667 \text{ B. T. U., nearly;}$$
$$170 \times 556 \times 0.111 = 10{,}502 \text{ calories} \quad \text{''}$$

and in mechanical units,

$$41{,}667 \times 772 = 32{,}167{,}924 \text{ foot-pounds, nearly;}$$
$$10{,}502 \times 423.55 = 4{,}448{,}122 \text{ kilog-metres, nearly,}$$

which is fifteen or twenty times the energy stored in the steam in a locomotive boiler in its normal condition, and about one-half as much as ordinarily exists in water and steam together. It is evident that the limit to the destructiveness of explosions so caused is the rate of transfer of this energy to the water thrown over the hot plate,

and the promptness with which the steam made can be liberated at the safety-valve. A sudden dash of water or spray over the whole of such a surface might be expected to even produce a "fulminating explosion." Fortunately, as experience has shown, so sudden a transfer, or so complete a development of energy, rarely, perhaps never, takes place.

16. **The Strength of Heated Metal** is known usually to decrease gradually with rise in temperature, until, as the welding or the melting point, as the case may be, is approached, it becomes incapable of sustaining loads. Both iron and steel, however, lose much of their tenacity at a bright red heat; at which point they have less than one-fourth that of ordinary temperature. A steam-boiler in which any part of the furnace is left unprotected by the falling of the water-level, is very likely to yield to the pressure, and an explosion may result from simple weakness. At temperatures well below the red-heat, this will not happen.

17. **Low Water,** in consequence of the obvious dangers which attend it and the not infrequent narrow escapes which have been known, has often been, by experienced engineers, considered to be the most common, even the almost invariable, cause of explosions. This view is now refuted by statistics and a more extended observation and experience; but it remains one of the undeniable sources of danger and causes of accident.

Its origin is usually in some accidental interruption of the supply of feed-water; less often an unobserved leak

or accelerated production of steam. Whatever the cause, the result is the uncovering of those portions of the heating-surface which are highest, and their exposure, unprotected by any efficient cooling agency, to the heat of the gases passing through the flue at that point. Should it be the case of a locomotive, or other boiler, having the crown-sheet of its fire-box so placed as to be first exposed, when the water-level falls, the iron may become heated to a full red-heat; if the highest surfaces are those of tubes, through which gases approximating the chimney in temperature are passing, the heat and the danger are less. In either case, danger is incurred only when the temperature becomes such as to soften the iron, or when the return of the water with considerable rapidity gives rise to the production of steam too rapidly to be relieved by the safety-valve or other outlet. Such explosions probably very seldom actually occur, even when all conditions seem favorable. Every boiler-making establishment is continually collecting illustrations of the fact that a sheet may be overheated, and may even alter its form seriously, when overheated, without completely yielding to pressure, and the Author has taken part in many attempts to experimentally produce explosions by pumping feed-water into red-hot boilers, and has but once seen a successful experiment. The same operation in the regular working of boilers has been often performed by ignorant or reckless attendants without other disaster than injury to the boiler; but it has unquestionably, on other occasions, caused terrible loss of life and

property. The raising of a safety-valve on a boiler in which the water is low, by producing a greater violence of ebullition in the water on all sides the overheated part, may throw a flood of solid water or of spray over it; and it is possible that this has been a cause of many explosions. The Author has seen but a single explosion produced in this way, although he has often attempted to produce such a result. In three experiments on a certain cylindrical boiler, empty, and heated to the red-heat, the result of rapidly pumping in a large quantity of water was, in the first, the production of a vacuum, in the second an excess of pressure safely and easily relieved by the safety-valve; and in the third case a violent explosion of the boiler and the complete destruction of the brick setting.* The boiler experimented upon was set in brickwork in the usual manner. In each experiment, the boiler was filled with water, a fire started, and, when the fire was in good order and the steam at the right point, all water was blown out; the boiler was allowed to become heated to the desired temperature, as indicated by a pyrometer inserted within it, and, at the proper moment, the feed-water was introduced by a force-pump. At each occasion, on the introduction of the water, the steam-pressure rose suddenly, the safety-valve opened, and, the water still continuing to enter, the boiler-pressure dropped almost as rapidly as it had risen, and the boiler cooled down on each occasion (except the last) without

* Sci. Am., Sept. 1875.

apparent injury, and without having even started a seam, although the metal had been red hot.

The last experiment resulted in the explosion of the boiler and the destruction of its setting, and interrupted the work. The succession of phenomena was in this case precisely as already described; but the temperature of the boiler was on this occasion higher, probably a bright red on the bottom, and the pressure of steam was about 60 lbs. before the explosion occurred. It had fallen somewhat from the maximum, attained the moment before. A committee of the Franklin Institute, conducting similar experiments,† had the same experience, the pressure "rising from one to twelve atmospheres within ten minutes," after starting the pump. The most rapid vaporization occurs, as is well known, at a comparatively low temperature of metal; at high temperature the spheroidal condition is produced, and no contact exists between metal and liquid.

Mr. C. A. Davis, President of the New York and Boston Steamboat Co., in a letter addressed, Dec. 7, 1831, to the Collector of the Port of New York, and concerning inquiries of the U. S. Treasury Department, wrote: *

"I have noted that by far the greater number of accidents by explosion and collapsing of boilers and flues, I might say seven-tenths, have occurred either while the boat was at rest, or immediately on starting, particu-

† Journal Franklin Inst., 1837, vol. 17.

* Report of Steam Boilers, H. R., 1832.

larly after temporary stoppages to take in or land passengers. These accidents may occur from directly opposite causes, either by *not letting off enough steam, or by letting off too much;* the latter is by far the most destructive."

The idea of this writer was that the "letting off of too much" steam, by producing low water, was the most frequent cause of explosions, an idea which has never since been lost sight of.

The chief engineer of the Manchester (G. B.) Steam Boiler Association, in 1866–89 repeatedly injected water into overheated steam-boilers, but never succeeded in producing an explosion.* Yet, as has been seen, such explosions may occur.

A writer in the Journal of the Franklin Institute,† a half century or more ago, asserted that "the most dreadful accidents from explosions which have taken place, have occurred from low-pressure boilers." It was, as he states, "a fact that more persons had been killed by low than by high-pressure boilers." Nearly all writers of that time attributed violent explosions to low water, and some likened the phenomenon to that observed when the blacksmith strikes with a moist hammer on hot iron.

Thus, if the boiler is strong, and built of good iron, and not too much overheated, or if the feed-water is introduced slowly enough, it is possible that it may not

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* Mechanics' Magazine, May, 1867; also Chief Eng'r's Report, Dec. 10, 1889.

† Vol. 3; pp. 335, 418, 420.

be exploded; but with weaker iron, a higher temperature, or a more rapid development of steam, explosion may occur. Or, if the metal be seriously weakened by the heat, the boiler may give way at the ordinary or a lower pressure, which result may also be precipitated by the strains due to irregular changes of dimension accompanying rapid and great changes of temperature.

Explosions due to low water, when there is a considerable mass of water below the level of the overheated metal, are sometimes fearfully violent, a boiler completely emptied of water, and only exploded by the volume of steam contained within it, is far less dangerous. Low water and red-hot metal in a locomotive or other fire-box boiler, are, for this reason, far more dangerous than in a plain cylindrical boiler; as was indicated by the experiments conducted by the Author, the latter must be entirely deprived of water before this dangerous condition can arise. In the course of the numerous experiments already alluded to, many attempts were made to overheat the latter class of boiler, but none were successful until the water was entirely expelled. Experiments, with apparatus devised for the purpose of keeping the steam moist under all circumstances, indicate that it is difficult, if not impossible, to overheat even an uncovered fire-box crown-sheet, if the steam be kept moist, and that such steam is very nearly as good a cooling medium, in such cases, as the water itself.

Figure 5 * represents a boiler exploded by the introduction of water, after it had been emptied by carelessly leaving open the blow-cock. This boiler was

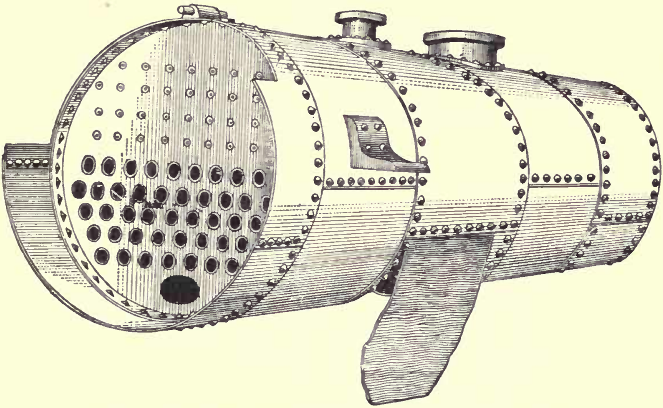

FIG. 5.—BOILER EXPLODED; CAUSE, LOW WATER.

about five years old, and the explosion, as is usual in such cases, was not violent, the small amount of water entering and the weakness of the sheet conspiring to prevent the production of very high pressure, or the storage of much energy. The whole of the lower part of the shell of the boiler was found, on subsequent examination, to have been greatly overheated. One man was killed by the falling of the setting upon him; no other damage was done.

Figure 6 shows the effect of a similar operation on a water-tube boiler. The feed-water was cut off, and not

* The Locomotive; Sept. 1886; p. 129.

noticed until the water-level became so low that the boiler was nearly empty and the tubes were overheated. One of the tubes burst, and the damage was speedily

FIG. 6.—TUBE BURST ; LOW WATER.

repaired at a cost of $15, and the works were running the next day.*

That low water and the consequent overheating of the boiler does not necessarily produce disaster, even when the water is again supplied before cooling off, was shown as early as 1811, by the experience of Captain E. S. Bunker of the Messrs. Stevens's steamboat "Hope," then plying between New York and Albany. During one of the regular passages, he discovered that the water had been allowed, by an intoxicated fireman, to completely leave both the boilers. He at once started the pump and, filling up the boilers, proceeded on his way, no other sign of danger presenting itself than "a crackling in the boiler as the water met the hot iron, the sound of which was like that often heard in a blacksmith's shop when water is thrown on a piece of hot iron." † A year later, Captain Bunker repeated this experience, at Philadelphia, on the "Phœnix,"

* G. H. Babcock.

† Doc. No. 21, H. R., 25th Congress, 3rd Session, 1838, p. 103.

[*To face page 70.*]

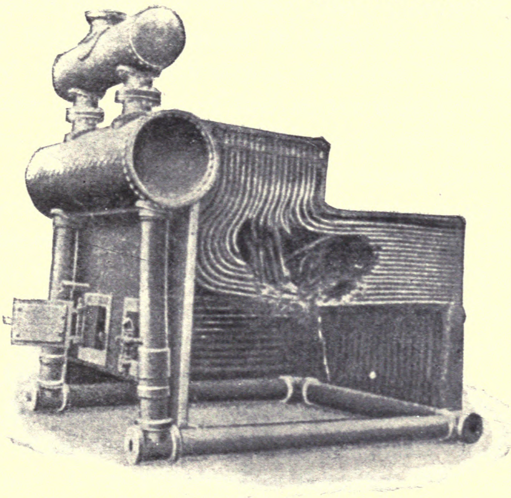

FIG. 6A.—AN UNEXPLAINED FAILURE.

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where the boilers where of the same number and size as those of the "Hope." *

Defective circulation may cause the formation of a volume of steam in contact with a submerged portion of the heating surface. The Author, when in charge of naval engines during the civil war, 1861–5, found it possible, on frequent occasions to draw a considerable volume of practically dry steam from the water-space between the upper parts of two adjacent furnaces at a point two or three feet below the surface-water level. After drawing off steam for a few seconds, through a cock provided to supply hot water for the engine and fire-rooms, water would follow as in the normal condition of the boiler. This condition often occurs in some forms of boiler and has been occasionally observed by every experienced engineer. It would not seem impossible, therefore, that steam might be sometimes thus encaged in contact with the furnace, and thus cause overheating of the adjacent metal. Many such instances have been related, but they have been commonly regarded by the inexperienced as somewhat apochryphal. †

In order that the danger of overheating the crown-sheet of the locomotive type of boiler may be lessened, it is very usual to set it lower at the fire-box end, when employed as a stationary boiler, so as to give a greater depth of water over the crown-sheet than over the

* Ibid.

† See London Engineer, Dec. 7, 1860, pp. 371, 403.

tubes at the rear. The plan of giving greatest depth of water, when possible, at that end of the boiler at which the heating-surfaces near the water-surface are hottest, is always a good one.

Mr. Fletcher concluded from his experiments that low water is only a cause of danger by weakening the overheated plates. He says:*

"These experiments, it is thought, may be accepted as conclusive that the idea of an explosion arising from the instantaneous generation of a large amount of steam through the injection of water on hot plates is a fallacy."

The conclusion of the Author, in view of the experiments of the committee of the Franklin Institute and of his own personal experience in the actual production of explosions by this very process, as elsewhere described, does not accord with the above; but it is sufficiently well established that low water may frequently occur and feed-water may be thrown upon the overheated plate without necessarily causing explosion. Danger does, however, certainly always arise, and such explosions have most certainly occurred—possibly many in the aggregate.

Low-water is certainly very rarely, perhaps almost never, the cause of explosion of other than fire-box boilers; in these, however, the danger of overheating the crown-sheet of the furnace, if the supply of water fails, is very great, and, in such cases, explosion is always to be feared. The most disastrous explosions are usually

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* London Engineer, March 15, 1867, p. 228.

those, however, in which the supply of water is most ample.

18. Sediment and Incrustation sometimes produce the effect of low-water in boilers, even where the surfaces affected are far below the surface of the water. Every increase of resistance to the passage of heat through the metal and the encrusting layer of sediment or scale causes an increase of temperature in the metal adjacent to the flame or hot gases, until, finally, the incrustation attaining a certain thickness, the iron or steel of the boiler becomes very nearly as hot as the gases heating it. Should this action continue until a red-heat, or a white-heat, even, as sometimes actually occurs, is reached, the resistance becomes so greatly reduced that the sheet yields, and either assumes the form of a "pocket," or depression, as often happens with good iron and with steel; or it cracks, or it even opens sufficiently to cause an explosion. "Pockets" often form gradually, increasing in depth day by day, until they are discovered, cut out, and a patch or a new sheet put in, or until rupture takes place. In such cases, the incrustation keeps the place covered while permitting just water enough to pass in to cause the extension of the defect.

In some cases, the process is a different and a more disastrous one. The scale covers an extended area, permitting it to attain a high temperature. After a time a crack is formed in the scale by the unequal expansion of the two substances and the inextensibility of the incrustation; and water entering through this crack is

exploded into steam, ripping off a wide area of incrustation previously covering the overheated sheet, and giving rise instantly, probably, to an explosion which drives the sheet down into the fire, and may also rend the boiler into pieces, destroying life and property on every side. Such an explosion usually takes place with the boiler full of water and its stored energy a maximum, and the result is correspondingly disastrous.

Certain greasy incrustations, and some flowery forms of mineral or vegetable deposits, have been found peculiarly dangerous, as, in even exceedingly thin layers, they are such perfect non-conductors as to speedily cause overheating, strains, cracks, leakage, and, often, explosion. M. Arago mentions a case in which rupture occurred in consequence of the presence of a rag lying on the bottom of a boiler.*

The effect of incrustation in causing the overheating of the fire-surfaces, the formation of a "pocket," and final rupture, is well shown in the three illustrations which follow.

When the water is fully up to the safe level, as at the right in the first of the three figures, the heat received from the furnace gases is promptly carried away by the water and the sheet is kept cool. When the water falls below that level, or is prevented, by incrustation, from touching the metal, as in the left-hand illustration, the sheet becomes red-hot, soft, and weak, and yields as shown. When this goes on to a sufficient extent, as on

* Report of the Committee of the Franklin Institute.

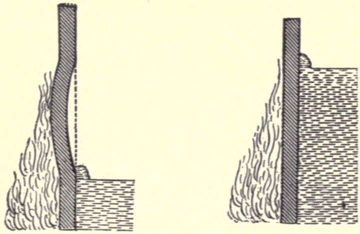

FIG. 7.—OVERHEATING THE SHEET.

a horizontal surface, figure 8, a pocket is produced. The illustration represents a sheet removed from the shell

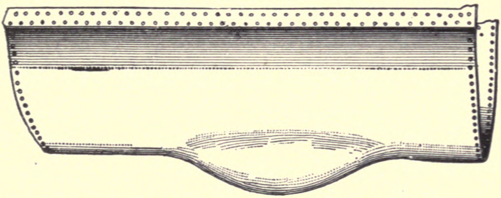

FIG. 8.—A "POCKET."

of an externally fired boiler, thus injured.

Finally, when the defect is not observed and the injured sheet removed, the metal may finally give way entirely, permitting the steam and water to issue, as in the last illustration of this series, in which the last step

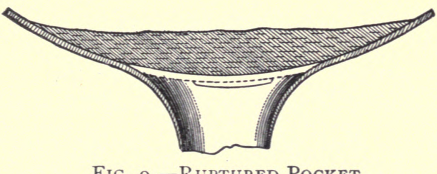

FIG. 9.—RUPTURED POCKET.

in the process is well represented. Where the area thus affected is considerable, the result may be a general breaking up of that portion of the shell, as in the next figure, and an explosion may prove to be the final step

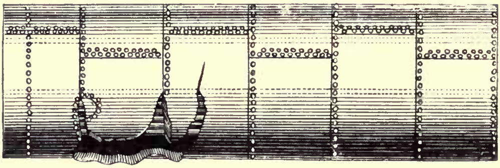

FIG. 10.—SHELL RUPTURED.

in the chain of phenomena described. In other cases where, as in the next sketch, a line of weakness may be

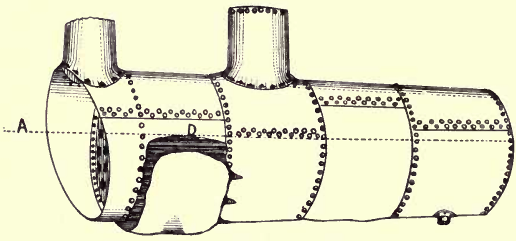

FIG. 11.—EXTENDED RUPTURE.

the result of other causes; a large section of the boiler may be broken out, as at *A D*, Figure 11.

The deposition of sediment and of scale takes place in the boiler. Not only in the boiler, but also with some kinds of water in the feed-pipe, as is illustrated in

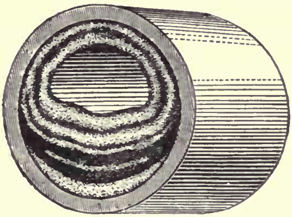

FIG. 12.—INCRUSTATION IN FEED-PIPE.

the accompanying engraving, which is made from an actual case in which the pipe was so nearly filled as to become quite incapable of performing its office. A current has apparently no effect, in many such cases, in preventing the deposition of scale. The Author has known hard scale to form in the cones of a Giffard injecter under his charge, where the steam was moving with enormous velocity, and loudly *whistling* as it passed.

Instances are well known of the explosion, with fatal effect of *open vessels*, in consequence of the action above described. Mr. G. Gurney, in 1831, gave an account of such an explosion of the water in an open cauldron at Meux's brewery, by which one person was killed and several others injured.* It was found that the bottom had become encrusted with sediment, and the sudden rupture of the film, permitting contact of the water above with the overheated metal below, caused such a sudden and violent production of steam that it actually

* Report on Steam Carriages ; Doc. 101, 22nd Congress, 1st Session, p. 31.

ruptured the vessel. The process of which this is an illustration is precisely analogous to suddenly throwing feed-water into an overheated boiler.

19. Energy Stored in Superheated Water has been sometimes considered a source of danger to steam boilers and a probable cause of explosions. The magnitude of this stock of energy is not likely to differ greatly from that of water at the same temperature under the pressure due that temperature, and, for present purposes, it may be taken as approximately unity. The quantity of heat so stored is, therefore, measured very nearly by the product of the weight of water so overheated, the mean range of superheating, and the specific heat here taken as unity. It is not known how large a part of the water in any boiler can be superheated, or the extent to which this action can occur. It is to be doubted, however, whether it can take place at all in steam-boilers.

To secure this condition the experiment of M.M. Donny, Dufour, and others show that the larger the mass of water, the less the degree of superheating attainable; the more impure the water, or the greater the departure from the condition of distilled water, and the larger the proportion of air or sediment mechanically suspended, the more difficult is it to attain any considerable superheating.

As early as 1812* Gay-Lussac observed a retarda-

* Ann. de Chemie et de Physique, lxxxii.

tion of ebullition in glass vessels; thirty years later,* M. Marcet found that water, deprived of air, can be raised several degrees above its normal boiling point, while Donny,† Dufour,‡ Magnus,§ and Grove †† all succeeded in developing this phenomenon more or less remarkably. Donny, sealing up water, deprived of air, in glass tubes, succeeded in raising the boiling point to 138° C. (280° F.), at which temperature vaporization finally occurred explosively. Dufour, by floating globules of pure water in a mixture of oils of density equal to that of the water, succeeded with *very minute* globules, in raising the boiling point to 173° C. (347° F.) at which temperature the normal tension of its steam is 115 pounds per square inch (nearly 8 atmospheres) by gauge. In such cases, the touch of any solid, or of bubbles of gas, would produce explosive evaporation. Solutions always boil at temperatures somewhat exceeding the boiling point of water, but usually quietly and steadily. In all these cases, the rise in temperature seems to have been greater the smaller the mass of water experimented with.

In all ordinary cases of steam-boiler operation, the mass of water is simply enormous as compared with the quantities employed in the above-described laboratory experiments; the water is almost never pure, and probably as invariably contains more or less air. It

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* Bibl. Univ., xxxviii.

† Ann. de Chemie et de Physique, 3ve, Seriet. xvi.

‡ Bibl. Univ. Nov. 1861, t. xii.

§ Poggendorff's Ann., t. cxiv. †† Cosmos, 1863.

would seem very unlikely that such superheating could ever occur in practice. There is, however, some evidence indicating that it may.

Mr. Wm. Radley* reports experimenting with small laboratory boilers of the plain cylindrical form, and continuing slowly heating them many hours, finally attaining temperatures exceeding the normal by 15° F. (8.3° C.) The investigator concludes:

"Here we have conclusive data suggesting certain rules to be vigorously adopted by all connected with steam-boilers who would avoid mysterious explosions: First, never feed one or more boilers with surplus water that has been boiled a long time in another boiler, but feed each separately. Second, when boilers working singly or fed singly are accustomed, under high pressure, to be worked for a number of hours consecutively, day and night, they should be completely emptied of water at least once every week, and filled with fresh water. Third, in the winter season the feed-water of the boiler should be supplied from a running stream or well; thaw water should never be used as feed for a boiler."

"Locomotive, steamboat, and stationary engine boilers have their fires frequently *banked up* for hours, without feeding-water, and the steam fluttering at the safety-valve, so as to have them all ready for starting at at a moment. This is a dangerous practice, as the foregoing experiments demonstrate. While so standing, all the atmospheric air may be expelled from the water,

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* London Mining Journal, June 28, 1856.

and it may thereby attain to a high heat, ready to generate suddenly a great steam-pressure when the feed-pump is set in motion. This is, no doubt, the cause of the explosion of many steam-boilers immediately upon starting the engine, even when the gauge indicates plenty of water. The remedy for such explosions must be evident to every engineer—keep the feed-pump going, however small may be the feed required."

On the other hand, the report of a committee appointed by the French Academy to inquire into the superheated water theory of steam-boiler explosions, indicates at least the difficulty of securing such conditions.* The committee constructed suitable apparatus, experimented in the most exhaustive manner, and investigated several explosions claimed by the advocates of the theory to have been due to this cause. They failed to superheat water under any conditions which could probably occur in practice, and the explosions investigated were shown conclusively to have resulted from simple deterioration of the boilers, or from carelessness.

It is unquestionably the fact that explosions due to this cause are at least exceedingly rare, although it is not at all certain that they may not now and then take place. The ocean is constantly being traversed by thousands of steamers having surface condensers and boilers in which the water is used over and over again, and in which is every condition seemingly favorable to

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*Annales de Mines, 1886.

such superheating of the water; but no one known instance has yet occurred of the production of this phenomenon, there or elsewhere, on a large scale, where boilers are in regular operation.

M. Donny, who first suggested the possibility of this action as a cause of boiler-explosions, has had many followers. M. Dufour,* who doubts if such explosions are possible in the ordinary working of the boiler, points out the fact, however, that boilers which are quietly cooling down, after the working hours are over, are peculiarly well situated for the development of this form of stored energy. He points out the known fact that many explosions have taken place under such conditions, the pressure having fallen below the working-pressure. M. Gaudry† makes the same observation. Such cases are supposed to be instances of "retarded ebullition," with decrease of pressure and superheating of the water. Many circumstances unquestionably tend to strengthen this view.

So tremendous are the effects of many explosions that M. Andrand has expressed the belief that a true explosion must be preceded by pressure approaching or exceeding 200 atmospheres,‡ an intensity of pressure, however, which no boiler could approximate. Mr. Hall, also, thinks that the shattering effect sometimes witnessed, resulting in the shattering of a boiler into small

* Sur l'Ebullition de l'Eau, et sur une cause probable d'Explosion des Chandiers a vapeur, p. 29.

† Traité des Machines à Vapeur.

‡ Comptes Rendes, May 1855, p. 1062.

pieces, must be the effect of a sudden and enormous force partaking of the nature of a blow,* and cites cases, such as are now known to be common, of an explosion taking place on starting an engine after the boiler has been at rest and making no steam for a considerable time. M. Arago cites a number of similar instances,† and Robinson a number in still greater detail.‡ Boilers, after quietly "simmering" all night, exploded at the opening of the throttle-valve or the safety-valve in the morning. The locomotive "Wauregan," which exploded within sight and hearing of the Author, at Providence, R. I., in February, 1856, is mentioned by Colburn as such a case. The engine had been quietly standing in the engine house two hours, the engineer and fireman engaged cleaning and packing, preparatory to starting out. The explosion was without warning and very violent, stripping off the shell and throwing it up through the roof, and killing the engineer, who was standing beside his engine.

Mr. Robinson§ thinks the usual cause of such explosions is the overheating of the water, the phenomenon being in its effects very like the "water-hammer" in steam-pipes, producing shocks which the Author has shown to give rise to instantaneous pressures exceeding the working-pressures ten or twenty times; the action,

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* Civil Engineers' Journal, 1856, p. 133; Dingler's Journal, 1856, p. 12.

† Annuaire, 1830.

‡ St. Boiler Explos., p. 62.

§ Ibid, p. 66.

however, seems rather to be that "boiling with bumping" familiar to chemists handling sulphuric acid in considerable quantities. Instances have been known in which this bumping has burst pipes or severely shaken boilers and setting without producing explosion.

The de-aeration of water, and the subsequent superheating of the liquid, to which some explosions have been attributed, are phenomena which have been often investigated. Mr. A. Guthrie, formerly U. S. Supervising Inspector General of Steam-vessels, states that he made many such experiments, as follows: *

"(1.) In my experiments, I first procured a sample of water from the boiler of an ordinary condensing engine; here, of course, in addition to being subjected to long-continued boiling, it had passed through the vacuum.

(2.) I procured a sample from the ordinary high pressure non-condensing engine boiler, which before entering the boiler had passed the heater at 210°.

(3.) I procured some clean snow and dissolved it under oil, so that there was no contact with the air.

(4.) I froze some water in a long, upright tube, using only the lower end of the ice when removed from the tube, and dissolved under oil.

(5.) I placed a bottle of water under a powerful vacuum pump worked by steam, for two hours; agitating the water from time to time to displace any air that might possibly be confined in it, then closed it by a stop-cock, so that no air could possibly return.

* American Artisan; Locomotive, 1880.

(6.) I boiled water in an open boiler for several hours, and filled a bottle half full, closed and sealed it up, so that when it became cool it would in effect be under a vacuum, agitating it as often as seemed necessary.

(7.) Another bottle was filled with the same, and sealed.

(8.) I next took some clean, solid ice, dissolved it under oil, and brought it to a boil, which was continued for an hour or more, after which it was tightly corked.

(9.) I procured a bottle of carefully distilled water, after long boiling and having been perfectly excluded from air during the distillation.

(10.) I obtained a large number of small fish, placed them in pure, clean water in an open-headed cask on a moderately cold night, so that very soon it became frozen over, consequently excluding the air, the fish breathing up the air in the water, so that (if I am correct in this theory) a water freed from air would be the result; but in *some* of these different processes, if not in all, I was likely to free the water from air, if it could ever possibly occur in the ordinary course of operating a steam boiler.

Having procured a good supply of glass boilers adapted to my purpose, and so made that the slightest changes could be noted, and using as delicate thermometers as I could obtain, I took these samples one after another, and brought them to the boiling point; and every one, with no variation whatever, boiled effectually and positively at 212° Fahrenheit or under; nor was

there the slightest appearance of explosion to be observed."

This evidence is, of course, purely negative.

The superheating of water, on even the small scale of the laboratory experiments of Donny, Dufour and others, has never been successfully performed except with the most elaborate precautions. The vessel containing the liquid must be absolutely clean; the washing of all surfaces with an alkaline solution seems to be one of the customary preliminary operations. The vessel must usually be heated in a bath of absolutely uniform temperature in order that currents may not be set up within the body of the liquid to be heated; no solid can be permitted to enter or come in contact with it; no shock can be allowed to affect it; even contact with a bubble of gas may stop the process of superheating. All these conditions are as far removed as possible from those existing in steam-boilers.

20. The Spheroidal State, or Leidenfrost's phenomenon, as it is often called, is a condition of the water, as to temperature, precisely the opposite of that last described, its temperature being less, rather than greater, than that due the pressure; while the adjacent metal is always greatly overheated, and thus becomes a reservoir of surplus heat-energy which can be transferred, at any instant, to the water. This peculiar phenomenon was first noted by M. Leidenfrost about 1746.

It was studied by Klaproth, Rumford, and Baudrimont,* and more thoroughly by Boutigny.

When a small mass of liquid rests upon a surface of metal kept at a temperature greatly exceeding the boiling point of the liquid under the existing pressure, the fluid takes the form of a globule if a very small mass, or of a flattened spheroid or round-edged disk if of considerable volume, and floats around above the metal, quite out of contact with the latter, and gradually, very slowly, evaporates. The higher the temperature of the plate, the more perfect this repulsion of the liquid. Should the temperature of the metal fall, on the other hand, the globule gradually sinks into contact with it, and, at a temperature which is definite for every liquid, and is the lower as it is the more volatile, finally suddenly absorbs heat with great rapidity and evaporates often almost explosively. If contact is forcibly produced at the higher temperature of the supporting plate of metal, as under a blacksmith's hammer, a real explosion takes place, throwing drops of the liquid in every direction.

M. Boutigny found the temperature of contact to be, for water, alcohol, and ether, respectively, 142° C., 134° and 61° (287° F., 273, and 142°). In all cases, the temperature of the liquid was independent of that of the metal and somewhat below the boiling point. It is found, also, that a real and powerful repulsion is produced between metal and liquid; this is supposed to be

* Ann. de Chemie et de Physique, 2d Series, t. lxi.

due, in part at least, to the cushion of vapor there interposing itself. Contact is accelerated by the introduction of soluble salts into the liquid.

It is supposed by many writers that this phenomenon may play its part in the production of explosions of steam-boilers, and especially in cases in which there seems some evidence that, immediately before the explosion, there was no apparent overheating of the parts exposed to the action of the fire, and in those still more remarkable instances in which the shattered parts had been, to all appearance, much stronger than other portions which had not been ruptured, no evidence existing of low-water or overheating at the furnace, and the pressure being, the instant before the accident, at or below its usual working-figure. Bourne * has no doubt that this does sometimes take place. Colburn gives a number of instances of explosions taking place under, apparently, precisely similar conditions, and Robinson † also cites several, in some of which the plates of the shell were badly shattered, as by a concussive force. In some such instances, evidence of overheating, but only far below the water-level known to have existed immediately before the explosion, have been observed, indicating repulsion to have there occurred. This latter is simply still another instance of bringing about the same results as when pumping water into an overheated boiler in which the water is low.

* Treatise on the Steam Engine, 1868.

† Steam Boiler Explosions, p. 33.

Mr. Robinson * tells of a case in which a nearly new locomotive, standing in the house, with a pressure, as shown but a moment before by the steam-guage, of but 40 pounds—one-third its presumed safe working-pressure—the fire low and everything perfectly quiet—exploded with terrible violence, shattering the top of the boiler, directly over the fire-box, into many parts. That such explosions might occur, were the metal actually overheated under water, is shown by experiences not at all uncommon.

In the work of determining the temperatures of casting alloys tested by the Author † for the U. S. Board appointed in 1875 to test iron, steel, and other metals, at the first casting, composed of 94.10 copper, 5.43 tin, while pouring of the metal into the water for the test, an explosion took place which broke the wooden vessel which held the water, and threw water and metal about with great violence. It appears probable that the metal was heated to an unusually high temperature, as in pouring other metals when at a dazzling white heat explosions sometimes took place, but they were usually not violent enough to do more than make a slight report as the hot metal touched the water. Another bar was cast at an extremely high temperature, being at a dazzling white heat. On pouring a small portion in water in attempting to obtain the temperature, a severe explosion took place, and this was repeated

* Steam Boiler Explosions, p. 62.

† Report on Copper-Tin Alloys, Washington, 1879.

every time that even a small drop of the molten metal touched the water. The cold ingot mould was then filled with this very hot metal. After the metal remaining in the crucible had stood for several minutes and had cooled considerably, it could be poured into water without causing the slightest explosion. Thus it would seem that the temperature at which contact with the water is produced may have an important effect upon the violence with which the steam is generated, and also that of the explosion so produced. The explosions sometimes taking place with fatal effect in foundries when molten metal is poured into damp or wet moulds are produced in the manner above illustrated. They are usually apparently of the "fulminating class." Another instance occurred within the cognizance of the Author, even more striking than either of the above. *

Feb. 2, 1881, two workmen in a gold and silver refinery were engaged in "graining" metal, which process consists in pouring a small stream of melted metal into a barrel of water, while a stream of water is also run into the barrel to agitate the water already there. Suddenly an explosion occurred which literally shivered the barrel and threw the workmen across the room. Every hoop of the barrel, stout hickory hoops, was broken. The staves, seven-eighths of an inch thick, and of oak, were not only splintered but broken across, and the bottom, which was resting on a flat surface, and which was of solid oak, an inch in thickness, was split

* Reported in the Providence (R. I.) Journal, Feb. 2, 1881.

and broken across the grain. A box, on which stood the man who was pouring the metal, was converted into kindling-wood. The metal, though scattered somewhat, for the most part remained in place, but the water was thrown in all directions.

This explosion of an open barrel, like the preceding cases, was evidently due to the deferred thermal reaction of the water with a mass of very highly heated metal, with which it was finally permitted to come in contact at a temperature which allowed an explosive formation of steam. This class of explosions, by which open vessels are shattered and the water contained in them "*atomized*," are by many engineers believed to exemplify the terrific "*explosions fulminantes*" of French writers on this subject. The temperature of maximum vaporization, with iron plates, was reported by the committee of the French Institute to be 346½° F. (175° C.), and that of repulsion 385° F. (196° C.), and to be the same under all pressures. Any cause which may retard the passage of heat from the iron to the water, though but the thinnest film of sediment, grease, or scale, may permit such increase of temperature as may lead to repulsion of the water, the overheating of the metal, the production of the spheroidal condition, and the accidents due to that phenomenon, *provided* that the fire be so driven as to supply more heat than can be disposed of in ordinary working by the circulation and vaporization then going on. Robinson's experiments with safety-plugs indicate that a good irradiation is usually a sufficient insurance against this

action; and experience with the boilers of locomotives and of torpedo-boats, in which from 50 to 100 pounds of coal per square foot (244 to 488 kilogs. on the square metre) of grate are burned every hour, shows that the risk, with clean boilers of good design, is not great. With impure water and defective circulation, Robinson observed many instances of singular and dangerous phases of this action.* It is suggested that many explosions of locomotives on the road, or at stations, may be due to the impact, on the shells of their boilers, of water thus projected from overheated iron below the water-line. In many such cases, the engines have not left the rails, the break taking place just back of the smoke-box, or near the fire-box, and from the impact of water thus thrown from the tube-sheets.

M. Melsen † experimentally proved it possible to prevent the occurrence of the spheroidal condition by the distribution of spurs, or points of iron over the endangered sheets.

The conductivity of the metal has been an important influence on the effect of contact, suddenly produced, between the red-hot solid and the liquid. Professor Walter R. Johnson observed, in his elaborate experiments,‡ that brass produced much greater agitation of the water when submerged at the red-heat than did iron. He also noted the singular fact that water at the

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* See his Steam Boiler Explosions, pp. 40-46.

† Bull. de l'Academie Royale de Belgique, April, 1871.

‡ Reports on Steam Boilers, H. R., 1832, p. 111.

boiling point, thrown upon red-hot iron, requires more time for evaporation than cold water, probably in consequence of the greater efficacy of the latter in bringing down the temperature of the metal to that of maximum rapidity of action. The contact with the iron of incrustation, oxide, or other foreign matter, accelerated this process, also. Johnson found that, beyond the temperature of maximum repulsion, vaporization was accelerated by further elevation of temperature.

At the meeting of the British Association in 1872, Mr. Barrett read a paper upon the conditions affecting the spheroidal state of liquids and their possible relationship to steam-boiler explosions. The presence of alkalies or soaps in water perceptibly aids in the production of the spheroidal state. A copper ball immersed in pure water produced a loud hissing sound and gave off a copious discharge of steam. On adding a little soap to the water, the ball entered the liquid quietly. Albumen, glycerine, and organic substances generally produced the same result. The best method is to use a soap solution, and to plunge into this a white-hot copper ball of about two pounds of weight. The ball enters the liquid quietly, and glow white hot at a depth of a foot or more beneath the surface. Even against such pressure, the ball will be surrounded with a shell of vapor an inch in thickness. The reflection of the light from the bounding surfaces of the vapor bubble surrounding the glowing ball, gives to the envelope the appearance of burnished silver. As the ball gradually cools, the bounding envelope become thinner, and finally

collapses with a loud report and the evolution of large volumes of steam. Mr. Barrett makes the suggestion that the traces of oil, or other organic matters which find their way into a steam-boiler, may similarly produce a sudden generation of steam sufficient to account for certain problematical explosions, and thus lends some strong confirmatory evidence to the idea often promulgated by others within and without the engineering profession.

21. Steady Rise in Pressure has been shown by the experiments of the committee of the Franklin Institute and by numerous cases of explosion, both before and since their time, to be capable of producing very violent explosions. In such cases, the steam being formed more rapidly than it is given exit, the pressure steadily increases until a limit is found in the final rupture of the weakest part of the boiler. Should this break occur below the water-line and be the result of local decay or injury, no explosion may ensue; but should the rupture be extensive, or should it occur above or near the surface of the water, the succession of phenomena described by Clark and Colburn may follow, and an explosion of greater or less violence may take place. The intensity of the effect will depend largely upon the quantity of stored energy liberated, and partly upon the suddenness with which it is set free. A slowly ripping seam, or gradually extending crack, would permit a far less serious effect than the general shattering of the shell, or an instantaneously produced and extensive rent.

The time required to produce a dangerous pressure is easily calculated when the weight of water present, W, the range of temperature above the working pressure and temperature, $t_1 - t_2$, and the quantity of heat, Q, supplied from the furnace are known, and is

$$T = \frac{W\,(t_1{}^1 - t_2{}^0)}{Q} f$$

Professor Trowbridge gives the following as fair illustrations of such cases: *

(1.) A marine tubular boiler of largest size, such that

$$w = 79{,}000 \text{ lbs. of water.}$$

Suppose the working pressure to be $2\frac{1}{2}$, and the dangerous pressure 4 atmospheres.

The boiler contains 6,000 square feet of heating surface; and supposing the evaporation to be 3 lbs. of water per hour for each square foot, we shall have, taking 1,000 units of heat as the thermal equivalent of the evaporation of 1 lb. of water,

$$t_1 - t = 29^\circ\ F.$$

$$Q = \frac{5000 \times 3 \times 1000}{60}$$

$$T = \frac{79000 \times 29}{\dfrac{5000 \times 3 \times 1000}{60}} = 9.1 \text{ minutes.}$$

(2.) A locomotive boiler, containing 5,000 lbs. of water, having 11 square feet of grate-surface, and burning 60 lbs. of coal per hour on each square foot of grate, each pound of coal evaporates about 7 lbs. of water per hour, making 77 lbs. of water evaporated per minute.

Suppose the working pressure to be 90 lbs. and the dangerous pressure to be 175;

$$t_1-t=50^\circ\ F.$$

$$T=\frac{5000\times 50}{77\times 1000}=3\tfrac{1}{2}\text{ minutes.}$$

(3.) *The Steam Fire-Engine.*—The boiler contains 338 lbs. of water and 157 square feet of heating-surface. Supposing each square foot of heating-surface to generate 1 lb. of steam in one hour, the pressure will rise from 100 to 200 lbs. in

$$T=7\text{ minutes.}$$

(4.) To find, in the same boiler, how long a time will be required to *get up steam;* that is, to carry the pressure to 100 lbs. If we suppose but $1\frac{1}{2}$ cubic feet of water in the boiler, we shall have

$$T=\frac{93\times 117}{\frac{157\times 1000}{60}}=4.1\text{ minutes.}$$

Thus, if W is diminished, the time t is diminished in the

same proportion. The lowering of the water-level from failure of the feed-apparatus increases the danger, not only by exposing plates to overheating, but by causing a more rapid rise of pressure for a given rate of combustion. Gradual increase of pressure can never take place if the safety-valve is in good order, and if it have sufficient area.

The sticking of the safety-valve, either of its stem or to its seat, the bending of the stem, or the jamming of the valve by a superincumbent object or lateral strain, and similar accidents, have produced, where boilers were strong and otherwise in good order, some of the most terrific explosions of which we have records. The parts of the boiler have been thrown enormous distances, and surrounding buildings and other objects levelled to the ground; while the report has been heard miles away from the scene of the disaster.

The records of the Hartford company, up to 1887, include accounts of 26 explosions of vessels detached from the generating boiler, used at moderate pressures, for various purposes in the arts, and there have been many others of less importance that were not considered worthy of public mention. It is concluded that the percentage of explosions among bleaching, digesting, rendering, and other similar apparatus is ten times greater than among steam-boilers at like average pressures, and the destructive work done is quite as astonishing as that by the explosion of ordinary steam generators. *

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[1] he Locomotive, 188/

This is sufficiently decisive of the question whether it is possible to produce destructive explosions simply by excess of pressure above that which the vessel is strong enough to withstand. In these cases, low-water, and all the other special causes operating where fire and high temperature exist, and such absurd theories as the generation of gas, or the action of electricity, are eliminated, and it is seen that mere deterioration and loss of strength, or a rise of steam-pressure, even where there is an ample supply of water, may produce explosions of the utmost violence.

22. **The Relative Safety of Boilers** of the various types, is determined, mainly, by their general design and their greater or less liability to serious and extensive injury by the various accidents and methods of deterioration to which all are to a greater or less extent liable. The two essential principles by which to compare and to judge the safety of boilers, are :

(1). Steam-boilers should be so designed, constructed, operated, inspected and preserved, as not to be liable to explosion.

(2). Boilers should be so designed and constructed that, if explosive rupture occurs at all, it shall be with a minimum of danger to attendants and surrounding objects.

The prevention of liability to explosion and the provision against danger should explosion actually take place, are the two directions in which to look for safety.

As Fairbairn has remarked, the danger does not con-

sist in the intensity of the pressure, but in the character and construction of the boiler.* Other things being equal, that boiler, or that form of boiler, in which the original surplus strength of form and detail is greatest, and which is at the same time best preserved, is the safest. That class in which original strength is most certainly and easily preserved, has an important advantage; those boilers in which facilities for constant oversight, inspection and repairs are best given, are superior in a very important respect to others deficient in those points. For example, the cylindrical tubular boiler, if properly set, is very accessible in all parts, and may be at all times examined; it offers peculiar facilities for inspection and the hammer-test, and can be readily kept in repair; but it is liable, in case of its becoming weakened by corrosion over any considerable area, or along any extended line of lap, to complete disruptive explosion.

On the other hand, the various "sectional," or so-called "safety" boilers, are rarely as convenient of access or of inspection, and cannot usually be as readily and completely cleaned; but they are so designed and constructed as to be little, if at all, liable to dangerous explosive rupture, and if a tube or other part bursts, it is not likely to endanger life or property. That boiler is, therefore, on the whole, best which is least liable to those kinds of injury which lead to explosion, and which is least likely to do serious harm should explosion actu-

*Engineering Facts and Figures, 1865.

ally take place.* Those who select the tubular boiler are commonly influenced mainly by considerations of cost, and the first of the above considerations; while the users of the water-tube sectional boilers are controlled by the second, so far as either considers this form of risk at all.

During the experiments of Jacob Perkins, about 1825 and later, the value of the "sectional" boilers, where high pressures are adopted, was well shown. He frequently raised his steam-pressure to one hundred atmospheres,† and in his earlier work rupture often took place, but no ill effects followed. The division of the boiler into numerous compartments saved the attendants from injury. In a letter to Dr. T. P. Jones, dated March 8, 1827,‡ Mr. Perkins states that he had worked at the above-mentioned pressure, with a ratio of expansion of 12; his usual pressure was about two-thirds that amount, and the ratio of expansion 8. Mr. Perkins was then building an engine to safely carry a pressure of 2,000 pounds per square inch.§

23. Defective Designs, causing explosion, are not as common as many other causes. They exist, however, more frequently than is probably usually supposed. The defects are generally to be observed in the staying

*Dr. E. Alban, following John Stevens, was probably the first to ennunciate the principle: "So construct the boiler that its explosion may not be dangerous." The High-Pressure Steam-Engine, 1847, p. 70.

† Jour. Franklin Institute, Vol. 3; p. 415.

‡ Ibid, p. 412.

§ Reports on Steam Boilers, H. R., 1832, p. 188.

of such boilers as require bracing; in the insertion of the heads of plain cylindrical boilers; in the attachment of drums and the arrangement of man-holes and hand-holes, and, less frequently, in the selection of the proper thickness and quality of iron for the shells and flues. Such defects as these are the most serious possible; they are not only serious in themselves, and at the start, but are of a kind which is commonly very certain to be exaggerated and rendered continually more dangerous with age. A thin shell grows constantly thinner, a weak stay or brace weaker, and an unstayed head more likely to yield every day; while a flue originally too thin is all the time overstrained, not simply by the steam-pressure, but also by the action of the relatively stronger parts around it. The most minute study of every detail, and the most careful calculation of the strength of every part, with an allowance of an ample factor of safety, are the essentials to safety in design.

Faulty design in bracing is illustrated by an explosion which took place in New York City, January 15th, 1881, by which, fortunately, however, no loss of life was caused. A dome-head, proportioned and braced as shown in the next figure, was blown out, and tore up a side-walk under which the boiler was set, doing no other damage. The case was reported on by Mr. Rose, substantially as follows:

"The dome-crown, tearing around the edge, at A, also tore across at B, being thus completely severed. The iron at the fractures was of excellent quality. The plate

showed lamination in places, and the crack around A was rusty and evidently not of recent formation.

The six stays, three of which are shown in place at C, Fig. 13, were all in position in the dome, and their sur-

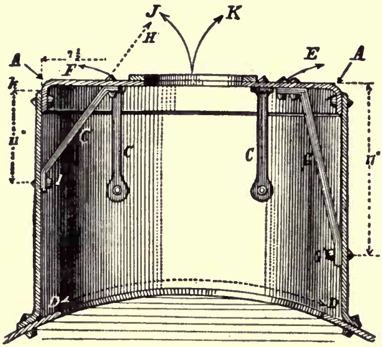


FIG. 13.—DOME AND HEAD.

faces of contact with the dome were covered by a black polish indicating movement and abrasion.

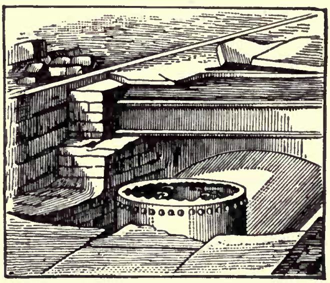


FIG. 14.—EXPLOSION OF DOME.

Apparently, as the pressure and temperature increased and decreased the dome-head might lift and fall, bend-

ing on A as a center. Thus taking I as a center, the movement of C would be in the direction of F, while at D the direction would be toward J, and the direction of motion of the two would nearly coincide.

The exploded dome shows an indentation at I, due to the motion of the foot of the stay.

Another error in the design of this boiler is that the diameter of the dome shell is 34 inches, and a circle of iron about 18 inches in diameter is punched out of the

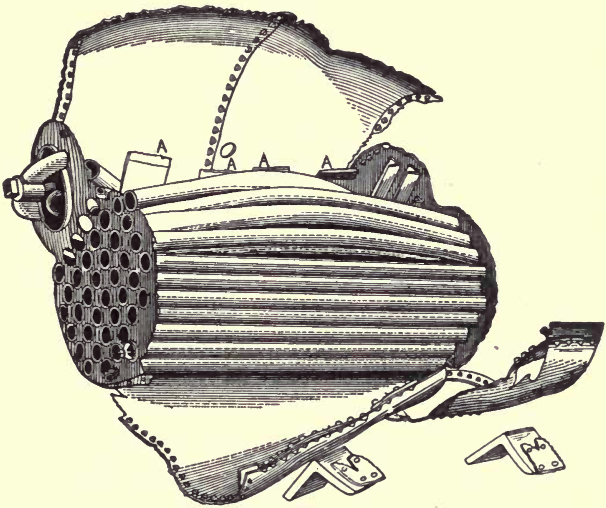


FIG. 15.—DEFECTIVE FORM.

shell at D. This opening is required only to admit an inspector or workman to the interior of the boiler, hence it is several inches wider than it should be.

Defective design is illustrated in the case of the boiler,

the explosion of which left it in the form shown in the engraving.*

This boiler consisted of two incompletely cylindrical shells, united as in the next figure, and ineffectively

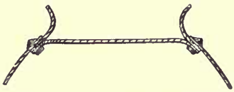


FIG. 16.—JUNCTION OF SHELLS.

stayed at the lines of contact. This is a form which, insufficiently braced, becomes peculiarly dangerous. In the case illustrated, the braces yielded, after having been weakened by continual alteration of form, and split the two shells apart as seen. It is probably possible to brace boilers of this type safely, but it is safer to avoid their use. They have sometimes been used for marine purposes, where lack of space compelled special expedients, the bracing consisting of strong bolts with nuts and washers on the outside of the shell; a comparatively strong and safe construction.

Steam-domes are a source of some danger and of additional expense, however well designed and attached, and it is probably good economy, all things considered, to dispense with them altogether, using a dry-pipe, instead, and expending the amount of their entire cost on an increase in size of boiler over that which would have otherwise been selected. The large boiler will steam easier and more regularly, will give dryer steam, and will be less liable to dangers of deterioration or of ex-

* Locomotive Feb., 1880.

plosion. A steam-drum above the boiler and connected by two separate nozzles, or a drum connecting the several boilers of a battery is not subject to the objections which apply to the attached dome.

24. **Defective Construction,** material and workmanship are responsible for many explosions of steam-boilers.

Thin, laminated, or blistered sheets, imperfect welds in bracing, the strains produced by the drift-pin, carelessness in the attachment of nozzles and drums, and in neglect of the precaution of straightening man-holes and hand-holes, and bad riveting, are all common causes of weakness and accidents. Only the most careful and skillful, as well as conscientious builders, can be relied upon to avoid all such faults, and to turn out boilers as strong and safe as the designs may permit. In all cases, careful and unintermitted inspection by an experienced, competent and trustworthy inspector, should be provided for by the proposing purchaser and user of the boiler. In the case of some of the more modern forms of boiler, constructed under a system of manufacture which includes some machine fitting and working to gauge of interchangeable parts, with regular inspection before assemblage, this supervision becomes less essential, and a careful test and trial previous to acceptance, may be all that is necessary to insure a satisfactory and safe construction. Whenever defective material or bad workmanship is detected, the fault should always be corrected before the boiler is accepted, and previous to any trial or use under steam. Careless riveting and the

use of the drift-pin are defects which cannot often be readily detected afterward, and they are such common causes of explosion that too much care cannot be taken to avoid any establishment of which the reputation, in this regard, is not the best.

Defective welds, the cause of many unfortunate accidents following the yielding stays or braces, are among the most common and least easily detected of all faults. They are due to the difficulty of producing metallic con-

FIG. 17.—DEFECTIVE WELDING.

tact in abutting surfaces between which particles of scale and superficial oxidation may interpose. The grain of the iron, as illustrated in the accompanying engraving, is broken at such junctions, and it is difficult to secure a good weld, and next to impossible to determine until it actually breaks, whether it is seriously unsound.

Defective workmanship is often exhibited most strikingly by the distorted forms of rivets, revealed after explosion has caused a fracture along the seams, or when the yielding of the weakened seam has resulted in an explosion. The following illustrations of a variety of

cases of such distortion, all taken from a single boiler,* show how very serious this kind of defect may be. It is not to be presumed that such carelessness, or worse, as is here exemplified, is to be attributed to the builder himself, but rather to the fault of the workmen carefully concealing their action from the eye of the foreman or inspector. No law or rule can protect the purchaser from this kind of fault; his only reliance must be upon the reputation of the maker and his workmen, and the vigilance and skill of his inspector.

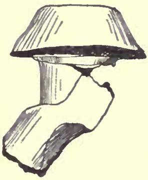


FIG. 18.

FIG. 18.—Rivet "driven" in over-set holes, the conical point broken off by the tearing apart of the plates, the head nearly severed from the body, and probably weakened in driving.

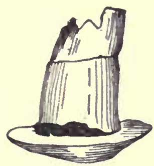


FIG. 19.

FIG. 19.—Rivet "driven" in over-set holes, heads broken off by the tearing apart of the plates, conical point also nearly broken off, bad sample of "driving," cone too flat to properly hold down the plate.

The next figure illustrates a group of similar distorted rivets which played their part in the production of an explosion.

In these instances it is seen that the defective rivet is usually evidence of either exceedingly bad workmanship in spacing and in assembling the sheets, the use of the drift-pin being shown, or of equally bad work in riveting up. Modern machine-work is seldom productive of such defects.

* Locomotive, Feb. 1880.

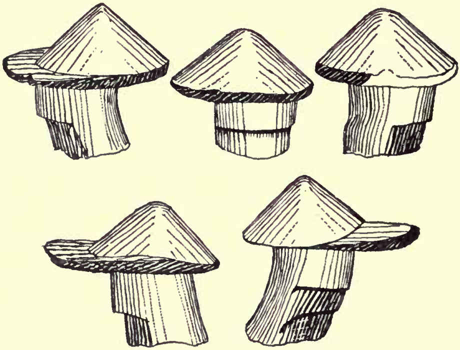


FIG. 20.—DEFECTIVE RIVETS.

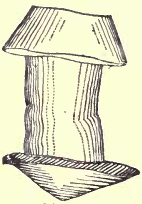


FIG. 21.

FIG. 21.—Rivet "driven" in slightly over-set holes, point eccentric and not symmetrical, too flat to properly secure the edge of the plate.

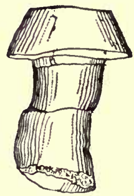


FIG. 22.

FIG. 22.—Rivet "driven" in badly over-set holes, very weak. See Figs. 23, 24 and 25, which were "sheared" at the time of the explosion. The dark shading on lower end Fig. 22 indicates an old crack.

FIGS. 23, 24, 25.—Samples selected from a number taken from a "sheared" seam, which was believed to be

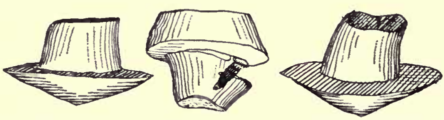


FIG. 23. FIG. 24. FIG. 25.

the initial break from which the explosion arose. They were no doubt similar to Fig. 22 before they gave way.

The Author, on one occasion, picked out with his fingers twelve consecutive rivets, deformed like those here illustrated, from a torn seam in an exploded boiler.

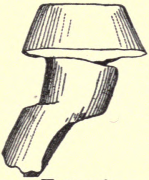


FIG. 26.

FIG. 26.—Rivet "driven" in over-set holes; it was probably fractured under the head in driving. Taken from a seam that was broken through the rivet holes.

FIGS. 27 and 28.—Long rivets taken from a broken casting which they were intended to secure to the wrought-iron head of the boiler. The holes in the wrought-iron plate were "drifted" and chipped to allow the rivets to enter, as shown by the enlarged portion of the body.

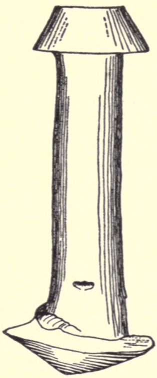


FIG. 27.

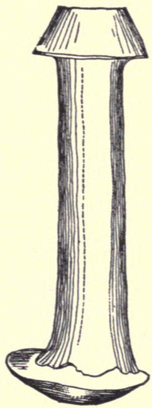


FIG. 28.

This irregular upsetting and the sharp little wave of iron on the body of Fig. 27 indicate the thickness of the wrought-iron plate.

25. **Developed Weakness,** usually a consequence of progressing decay by corrosion, is the most common of all causes of the explosion of steam-boilers. A boiler, designed and constructed of the best possible proportions and of the best of materials, having at the start a real factor of safety of *six*, may be assumed to be as safe against this kind of accident as possible; but, with the beginning of its life, decay also begins, and the original margin of safety is continually lessened by a never ceasing decay. The result is an early reduction of this margin to that represented by the difference between the working-pressure and that fixed as a maximum by the inspector's tests. Should this difference be sufficient to insure against accident, resulting from further depreciation, in the interval between inspector's or other tests, explosion will not occur; should this margin not be sufficient, danger is always to be apprehended, and, almost a certainty that rupture, and possibly explosive rupture, will at some time occur. The margin is legally, usually fifty per cent.; it is too small to permit the proprietor to feel a real security. It is usually thought that the tests should show soundness under pressure, at least at double the regular working-pressure at which the safety-valve is set.* Many cases have been known in which the boiler has yielded at the

*Experiments made by the Author, and later, by other investigators, have indicated the possibility that an apparent factor of safety of *two*, under load momentarily sustained, may not actually mean a factor exceeding one for permanent loading. Materials of Engineering, Vol. I., §133; Vol. II., §295.

working-pressure not very long after the regular official inspection had taken place.

Such an example was that of the explosion of the boiler of the "Westfield," in New York harbor, in June, 1876. The steam ferry-boat "Westfield," is one of three boats which have formed one of the regular lines between New York and Staten Island. The "Westfield" made her noon trip up from the Island to the city, on Sunday, July 30th, and while lying in the New York slip, her boiler exploded, causing the death of about one hundred persons and the wounding of as many more.

The boiler is of a very usual form, as represented in Fig. 29, and is known as a "Marine return-flue boiler." The diameter of its shell—the cylindrical part was ruptured—is ten feet: its thickness, No. 2 iron, twenty-eight hundredths of an inch.

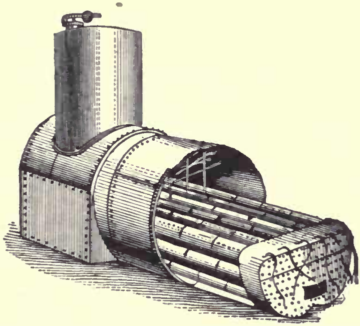


FIG. 29.—BOILER OF THE WESTFIELD.

The evidence indicated that the explosion occurred in consequence of the existing of lines of channeling and long existing cracks, by which the boiler was gradually

so weakened, that, six weeks after its inspection and test, the pressure of steam being allowed by the engineer to rise slightly above the pressure allowed, the boiler was ruptured, giving way along a horizontal seam and tearing a course out of the boiler.

The common lap-joint, customarily adopted in the construction of boilers, is liable to such serious distortion under very heavy pressure, as to produce leakage before actually yielding, and this leakage is sometimes so great as to act as a safety-valve. Thus, suppose a straight strip of plate riveted up in parts as in Fig. 30.* A heavy pull will cause distortion as shown, in all cases except where a butt-joint is made with a covering string on each side. If the metal is brittle, and the rivet-heads strong, preventing the bending of the plate on the line of rivet-holes, the plate will probably break adjacent to G or F, Fig. 30; or in the middle, I and H. But should the plates be ductile or the rivet-heads weak, the break would occur at the line through the holes.

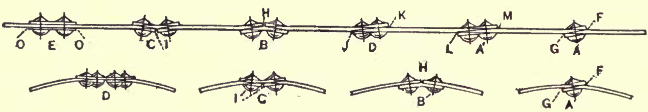


FIG. 30.—YIELDING JOINTS.

If the plates, Fig. 30, A, etc., were straight at the joint, the extreme end, L, must contract and the outer one expand at M, involving in the one a compression or upsetting, and in the other drawing the metal. If the

* See Locomotive, Oct., 1880.

joint be a butt, with a single outer cover, C, a similar contraction must take place at both ends and a contraction of the middle of the covering strip, while the opposite would take place in the case of the joint with the inner cover, B; these distortions are not likely to take place in a *transverse* seam of a cylindrical boiler shell from internal pressure. The butt-joint, with two covering-plates, E, would retain its shape.

The next Figures, 31, 32, show the effect of strain on rivet-holes, and on holes filled by the rivet. Lapped

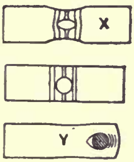
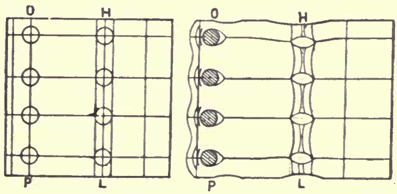


FIG. 31.



Before Stretching. FIG. 32. After Stretching.

longitudinal joints are shown at A′, Fig. 30. Single-riveted and single-covered butts at B′ and C′. D′ shows a double-riveted single-covered butt.

Multiple Explosions are not infrequent. They usually occur in consequence of the explosion of one of a battery, with the result of injuring adjacent boilers in such a manner that they explode, the phenomena following each other so quickly, as to produce the appearance of simultaneous explosion. It is possible, also, that, in some cases, an accession of pressure in a set of boilers, may take place with such suddenness as to explode several, notwithstanding there may exist a difference in their resisting power; the weakest *not* be-

ing given time to act as a safety valve to the rest. It is doubtful, however, whether such cases can often, if ever, arise.

26. **General and Local Decay** introduces vastly different degrees and elements of danger. As has been elsewhere stated, in effect, an explosion comes of extended rupture; while local injuries or breaks, if they do not lead to wider injury, cannot cause widespread disaster. Hence, general corrosion, extending over considerable areas of plate, or along lines of considerable length, is a cause of danger of complete disruption and explosion. A corroded spot in a fire-box, a loosened rivet, or even a broken stay, if the boiler be otherwise well-proportioned, well-built, and in good order, may not be a serious matter, but a thinned sheet in the shell, a long groove under a lap, a line of loose rivets, or a cluster of weakened stays or braces, will certainly be most dangerous. General or widespread corrosion is very liable to lead to explosion; local and well-guarded corrosion may cut quite through the metal and simply cause a leak or an unimportant "burst." Old fire-boxes are often seen covered with "patches" in places, and yet they very rarely explode. Such a state of affairs may, nevertheless, by finally producing large areas of patched and fairly uniformly weak portions of the boiler, lead to precisely the conditions most favorable to explosion. A steam-boiler experimentally exploded at Sandy Hook, N. J., Sept., 1871,* had previously, by

* Journal Franklin Institute, Jan., 1872.

repeated rupture, by hydraulic pressure and patching, been gradually brought into precisely this state, and exploded under steam at 53½ pounds, about four atmospheres pressure, a slightly lower pressure than it had sustained (59 pounds) at its last test. On this occasion, when a pressure was reached of 50 pounds per square inch, a report was heard which was probably caused by the breaking of one or more braces, and at 53½ pounds, the boiler was seen to explode with terrible force. The whole of the enclosure was obscured by the vast masses of steam liberated; the air was dotted with the flying fragments, the largest of which—the steam drum—rising first to a height variously estimated at from 200 to 400 feet, fell at a distance of about 450 feet from its original position. The sound of the explosion resembled the report of a heavy cannon. The boiler was torn into many pieces, and comparatively few fell back upon their original position.

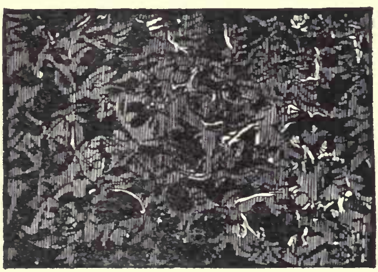


FIG. 33.—CORROSION.

Thus corrosion may affect a single spot in a boiler, in which case a "patch," if properly applied, should make

the boiler nearly as strong as when whole. A series of weak spots near each other may so weaken a boiler as to produce explosion, as may any considerable area of thin plate, although, when occuring in the stayed surfaces of a fire-box, the metal may become astonishingly thin. A sketch of spots of corrosion is shown in Fig. 33, which represents the cause of an actual explosion. This cause of explosion may be either internal or external, and is produced internally by bad feed-water, and externally by dampness or by water leaking from the boiler, either unseen or neglected. It is always dangerous to have any portion of a boiler concealed from observation.

The effect of covering a part of a sheet subject to corrosion by solid iron, as by the lap of a seam, is shown in the next figure, which also exhibits a common method

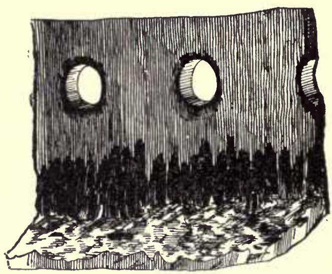


FIG. 34.—CORROSION AT A SEAM.

of corrosion along a seam. The same effect is seen still more plainly in the succeeding figure, in which the pitting which so often attends the use of the surface condenser is also well shown.

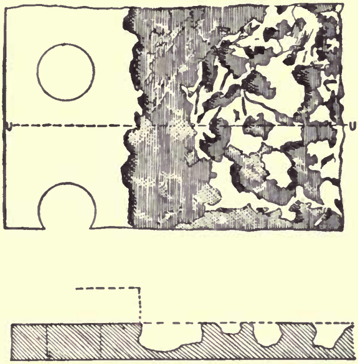


FIG. 35.—PITTING.

27. **The Methods of Decay** are as various as the forms and locations of the parts subject to corrosion. As Colburn* has said " As a malady, corrosion corresponds in its comparative frequency and fatality, to that great destroyer of human life, consumption," and it has as innumerable phases and periods of action. The two most common methods of decay are the general, and here and there localized, corrosion, that goes on in all boilers, and, in fact, on all iron exposed to air and carbonic acid presence of moisture; and the concentrated and localized oxidation that is often seen along the line of a seam, at the edge of the lap, where the continual changing of form of the boiler is as constantly producing an alternate flexing and reflex motion of the sheet which throws off the oxide as fast as formed along that line, and exposes fresh, clean metal to the corroding influence.

* Trans. Brit. Assoc., 1884.

A groove or furrow is thus, in time, produced, which may, as occurred in the case of the "Westfield," Fig. 36, actually cut through the sheet before explosion takes place.

The phenomenon known as "grooving" or "furrowing" is well illustrated by the case just mentioned, in which this action was originally started, probably by the carelessness of the workman, who, either in chipping the edge of the lap along a girth seam, or in caulking the seam, scored the under sheet along the edge of the lap with the corner of his chisel, or with the caulking-tool. This is a very common cause of such a defect.

The boiler was broken into three parts. The first, and by far the largest part, consisted of the furnaces, steam-chimney and flues, with a single course of the shell; the second consisted of two courses of the outside shell next the back head, together with that head, to which they remained attached; the third piece consisted of a single complete course from the middle of the cylindrical shell, which was separated at one of its longitudinal seams, partially straightened out and flung against the bottom and side of the boat. The last piece remained opposite its original position in the boiler, before the explosion, while the first and second pieces went in opposite directions, the former finally lying several feet nearer the engine than when in *situ*, and against the timbers of the "gallows-frame," while the latter piece was thrown fifty feet forward into the bow of the boat, where it fell, torn and distorted. The longitudinal seam, along which piece number three separated, and the deep score or

"channel" cutting nearly through in many places, and presenting every evidence of being an old flaw, were plainly seen. The mark made by a chisel in chipping, and that of the caulking-tool, were seen, and indicated the probable initiative cause of the flaw.

The Author examined this piece and found an old crack or "channel" cut, along the edge of the horizontal lap referred to as being at the ends of the sheet, and in some places so nearly through that it was difficult to detect the mere scale of good iron left, while in other places there remained a sixteenth of an inch of sound metal. Fig. 36 exhibits a section of the crack.

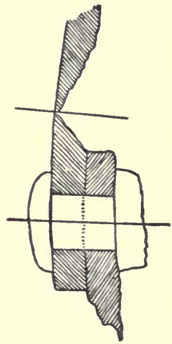


FIG. 36.
GROOVING.

Were this the weakest part in the boiler, and the *least thickness* here one-sixteenth of an inch, the tensile strength being equal to the average determined by the tests to be described, the pressure required to rupture such a boiler, ten feet in diameter, would be $44079 \times 1\text{-}16 \times 2 \div 120 = 47$ lbs. per square inch, nearly. A pressure of twenty-seven pounds would burst it open where the least thickness was slightly more than one-thirty-second of an inch. One portion may be supported, to some extent, by a neighboring stronger part. Along this longitudinal seam the limit of strength would seem to have been about thirty pounds per square inch, which is about the pressure at which the boiler exploded, this seam ripping for a distance of several feet.

[To face page 121.]

FIG. 36A.—RESULTS OF EXPLOSION OF TUBULAR BOILER

Sometimes this action produces a narrow crack, and at other times, as above stated, as the rust formed is thrown or scoured off the iron at the bend, leaving a comparatively clean surface, oxidation is probably accelerated, and the fault takes the form of a groove or furrow. If unperceived, this goes on until a rupture or an explosion occurs.

Of forty explosions of locomotive boilers noted in British Board of Trade reports,* eighteen gave way at the fire-box and twenty at the barrel. Of these twenty, every one was the result of "grooving" or cracks along the lap of seams, all of which were lap-joints. The grooves were most common; they always occurred along the edge of the inside over-lap, just where the changes of form with varying pressure would concentrate their effects. Such results are sometimes also seen at butt-joints, especially where a strip has been used inside. The racking action of the engines may produce precisely the same effect. Wherever change of form is felt, grooving or furrowing, and cracking, may be expected to be found in time. Where the boiler is already heavily strained along one of these lines of reduced thickness, any slight added stress, as a jar, or the action of a caulking-tool, as where leaks in boilers under pressure are being caulked, may precipitate an explosion, the break following the groove or crack just as a stretched drum-head may yield to the scratch of a knife.

* Wear and Tear of Steam Boilers; F. A. Paget, Trans. Soc. of Arts, 1865. London, 1865, p. 8.

28. Differences in Temperature between parts of a boiler more or less closely connected in the structure may produce serious strains, and some instances of explosion have been attributed to this cause.

Changes of temperature occur as steam is raised or blown off from a boiler, and its temperature at one time becomes that due the steam-pressure, and then it falls to that of the atmosphere each time that steam is blown off. It will change its form more or less, and will usually be subjected to some strain by this process. Again, while actually at work, the steam-space and upper portion of the water-space are at the temperature of steam at the working-pressure, while the lower part is continually varying in temperature from that of the feed-water to the maximum which it attains after entrance. This difference of temperature between the upper and lower parts of the boiler, as well as between other portions, causes a continual tendency to distortion, and, if this distortion be resisted, a stress is thrown upon the parts equal to that which would be required, acting externally, to remove the distortion, if produced. The stress is also equal to the mechanical force that would be necessary to produce similar distortion.

Thus, had the temperature of the main and upper part of the "Westfield's" boiler been, after the entrance of the feed-water, 273°, or that due to about twenty-seven or twenty-eight pounds steam, while the feed-water having a temperature of 73°, the bottom of the boiler having a temperature, in consequence, 200° below that of the top, the difference in length would be about

one-eight-hundredth, and, if confined by rigid abutments, iron so situated would be subject to a stress of twelve and a half tons per square inch. But, in this case, one part would yield by compression and the other by extension, and if they were to yield equally it would reduce the stress to six and a quarter tons. Actually, in this case, the lower fourth and upper three-fourths would be likely to act against each other, and the stress, if the boiler had no elasticity of form, would be about nine tons. Any elasticity of form—and boilers generally possess considerable—would still further reduce the strain, and it very frequently makes it insignificant.

It is thought, by more experienced engineers and other authorities, that many of the explosions known to have taken place, after inspection and test, at pressures lower than those of the test, are caused by the weakenening action of unequal expansion, the stresses and strains produced in this manner being superadded to those due to simple pressure, against which latter the boiler might otherwise have been safe. Such defects may also be the final provocation to explosion when cold feed-water is pumped into a boiler, on getting up steam, or possibly, sometimes, when cooling off. It has even been asserted that an empty boiler has been ruptured by such changes of form consequent on building a light fire of shavings in a flue to start the scale. The Author has known of instances in which the girth-seams of large new marine flue-boilers were ruptured along the line of rivet-holes a distance of several feet by the intro-

duction of a large volume of cold feed-water, when steam was up, but the engine at rest.

The differences of temperature on the two sides of the sheet may be important. While it is true that the heat supplied by the furnace-gases is absorbed by the boiler to the same extent, practically, without much regard to the thickness of the plates of the boiler, it is a well-known fact that the resistance of iron to the flow of heat is so great that the effect of heat on the metal itself is seriously modified by the thickness of the sheet. Heavy plates "burn" away, projecting rivet-heads are destroyed and the laps of heavy plates are especially liable to be thinned seriously where they are employed.

A variation of temperature of considerable range, and often recurring, frequently causes injury by hardening the metal of the boiler, making it brittle and liable to crack with change of form, and also produces the very change of form causing this cracking. The experiments of Lt.-Col. Clark, R. A.,* show that great distortion may be thus produced. It is probably thus that iron, and especially steel, fire-boxes so often crack, in consequence of a continual swelling of the metal under varying temperatures and the stresses so caused. This action, combined with oxidation, external and internal, sometimes makes the plates, and often the stays, of the boiler remarkably weak and brittle; they sometimes become more like cast than wrought-iron. The thicker the sheet, the more readily is it overheated and over-strained.

* Proc. Royal Society, 1863; Jour. Franklin Inst., 1863.

The extent to which alteration of form under pressure may go, with good material before actual rupture, is illustrated by the following:*

During the summer of 1868 a cylindrical boiler, made of 1/4 inch steel plates, built at the Fort Pitt Iron Works, Pittsburgh, was tested under authority of the government, with a view to determining the relative advantages of steel and iron as a material for navy boilers. When the pressure of cold water had reached 780 lbs., the "girt" of the boiler was found to have permanently increased 3 3/4 inches, and at 820 lbs., rupture occurred.

Cases have been known in which a steel crown-sheet has become overheated, and has sagged down until, the tube-sheet going with it, a basin-shaped form has been produced, convex toward the fire, and yet no fracture produced, even when the pump was put on and the boiler filled up again under pressure.

29. **The Management of the Steam-Boiler**, or, more correctly, its mismanagement, while in operation, and a neglect of proper supervision and inspection, may be considered, on the whole, the usual reason of explosion, as the deterioration of the boiler is the immediate cause, and this deterioration is almost invariably so gradual and so readily detected by intelligent and painstaking examinations that there is rarely any excuse for its resulting disastrously. A well-made boiler, under good management and proper supervision, may be considered as practically free from danger.

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* Iron Age, Sept. 26, 1872.

The person in direct charge of the boiler is usually a presumably experienced and trustworthy man. He should be thoroughly familiar with his business, generally intelligent, of good judgment, ready and prompt in emergencies, and absolutely reliable at all times. His first duty is to see that the boiler is full to the water-line, trusting only the gauge-cocks; he must keep constant watch of the furnaces, flues and other surfaces subject to the action of the fire, and thus be certain that no injury is being done by overheating or sediment; he must keep the feed-apparatus in perfect working order, keep up the supply of water continuously and regularly, and see that the safety-valve is in good order at all times. Such careful management, conscientious inspection and cleaning, and repairing at proper intervals, will insure safety.

To keep the safety-valve in good working order and to make certain that it is operative, provision should be made for opening it by hand, and it should be daily raised, before getting up steam, to the full height of its maximum lift.

Explosions of gas sometimes precipitate steam-boiler explosions. Should the gases leaving the fuel and the furnace not be completely burned, but become so mingled in the flues as to produce an explosive mixture, combustion finally occurring, the shock may be sufficient to cause rupture of the boiler, and, as has actually sometimes happened, its explosion. Sewer gases have been known to find their way into an empty boiler through an open blow-off pipe, and have been exploded by the

first light brought to the manhole, and with serious damage to adjacent property. Mineral oils used to detach scale have caused similar dangerous and sometimes fatal explosions by the ignition of the mixture of their vapors and the air within the boiler. It is important that care be taken in using lights about boilers in such cases of application of mineral oils.

Explosions of gas within a boiler at work cannot occur; but the suggestion of the possibility of such an occurrence is often made. No decomposition of water can take place except a portion of the boiler is overheated; this happening, all the oxygen produced is absorbed by the iron, and no recombination can occur later, even were it possible for ignition to take place under the conditions producing decomposition.

The flooding of a boiler with water until it is filled to the steam-pipe, or safety-valve, may cause so serious a retardation of the outflow of the mingled fluids as to result in overpressure and great danger. Mr. W. L. Gold * gives the following instances, and the experience of the Author justifies fully his statement. The steam-pipe or the safety-valve cannot relieve a full boiler rapidly and safely.

First, a boiler 38 inches in diameter, two flues, shell ¼ inch Juniata iron, ruptured in the sheet a crack 9 inches long, steam gauge indicating 60 lbs., safety-valve weighted at 80 lb. pressure. This rupture closed instantly, and if he had not seen it made, he might possi-

* Am. Manufacturer, Feb., 1881.

bly have been surprised by an explosion, with water and steam in their normal condition, very shortly after. Second, a steam-drum (spanning a battery of five boilers) 30 inches in diameter. The blank-head forced (bulged) out, the 1 ½ inch stay-rods stretched, and the corner of the head-flange cracked one-third around. Third, a vertical boiler, built especially to carry high pressure (safe running pressure 150 lbs.), the hand-hole and man-hole joints forced out past the flanges, the steam-pipe joints and union forced out, the packing in the engine piston destroyed, and the engine generally racked, so as to be almost useless. Steam pressure by gauge from 40 to 60 lbs.; safety-valve weighted at 90 lbs.

Mr. Gold suggests that, as this is a not infrequent occurrence, many explosions may be simply the final act in the drama commenced by the feed-pump.

30. Emergencies must be met with a clear head and ready wit, with perfect coolness, and, usually, with both promptness and quickness of action. Every man employed about steam-boilers, as well as every engineer and every proprietor, should have carefully thought out the proper course to take in any and every emergency that he can conceive of as likely or possible to arise, and should have constantly in mind the means available for meeting it successfully. When the time comes to act, it is not always, or even often, possible to take time to study out the best thing to be done; action must be taken, on the instant, based on earlier thought or on either the intuition or the impulse of the moment.

"*Low-water*" presents, perhaps, the most common,

as well as one of the most serious, of such emergencies. The instant it is detected, the effort must be made to check the fall to a lower level; the fire must be dampened, preferably by throwing on wet ashes, and the boiler allowed to cool down. Care should be taken that the safety-valve is not raised so as to produce a priming that might throw water over the heated metal, and that no change is made in the working of either engine or boiler that shall produce foaming or an increased pressure. If, on examination, it is found that the water has not fallen below the level of either the crown-sheet or any other extended area of heating surface, the pump may be put on with perfect safety; but if this certainty cannot be assured, the boiler should be cooled down completely, and carefully inspected and tested, and thoroughly repaired, if injured. If no part of the exposed metal is heated to the red-heat there is no danger, except from a rise in the water-level and flooding the hot iron. If any portion should be red-hot, an additional danger is due to the steam-pressure, which should be reduced by continuing the steady working of the engine while extinguishing the fire. If the safety-valve be touched at such a time, it should be handled very cautiously, allowing the steam to issue very steadily and in such quantities that the steam-gauge hand shows no fluctuation, while steadily falling. The damping of the fire with wet ashes will reduce the temperature and pressure very promptly and safely. The Author has experimentally performed this operation, standing by a large outside-fired tubular boiler while

all the water was blown out, and then covering the fire. The pyrometer inserted in the boiler showed no elevation of temperature until all the water was gone, and the fire was then so promptly covered that the rise was but a few degrees and the boiler was not injured. As it proved, there was not the slightest danger in that case; but with less promptness of action some danger might have arisen of injuring the boiler, although not of explosion.

Overheated plates, produced by sediment, or over-driving, resulting in the producing of "pockets" or of cracks, are, virtually, cases of low-water, and the action taken should be the same. The boiler being safely cooled down, the injured plate should be replaced by a sound sheet, all sediment or scale carefully removed, and a recurrence of the causes of the accident effectively provided against.

Cracks, suddenly appearing in sheets exposed to the fire or elsewhere, sometimes introduce a serious danger. The steps to be taken in such a case are the immediate opening of the safety-valve and reduction of steam-pressure as promptly and rapidly as possible, meantime quenching the fire and then cooling off the boiler and ascertaining the extent of the injury and repairing it. In such a case, unless the crack is near the safety-valve itself, no fear need be entertained of too rapid discharge of the steam.

Blistered sheets should be treated precisely as in the case preceding. It is not always possible to surmise the extent of the injury or the damage involved until

steam is off and an examination can be made. It is not, however, absolutely necessary to act as promptly as in the preceding cases; and, when the blister is not large and is not extending, it is sometimes perfectly allowable to await a convenient time for blowing off steam and repairing it.

An inoperative safety-valve, either stuck fast, or too small to discharge all the steam made, or to keep the pressure down to a safe point, produces one of the most trying of all known emergencies. In such a case, steam should be worked off through the engine, if possible, and discharged through any valves available, through the gauge-cocks, or even through a few scattered rivet-holes, out of which the rivets may be knocked on the instant; the fire being in the meantime checked by the damper, or by free use of water. The throwing of water into a furnace is often a somewhat hazardous operation, however, and, if necessary, should be performed with some caution, to avoid risk of injury of either the person attempting it or of the boiler. The use of wet ashes is preferable. In all cases in which it is to be attempted to reduce the rate of generation of heat, closing the ashpit-doors as well as opening the fire-doors will be of service by checking the passage of hot air from below and accelerating the influx of cold air above the grate; but the closing of the ashpit involves, with a hot fire, some risk of melting down the grates.

31. The Results of Explosions of steam-boilers, in spreading destruction and death in all directions, are so familiar as scarcely to require illustration; but a few

instances may be described as examples in which the stored energy of various types of boiler has been set free with tremendous and impressive effect.

Referring to the table in § 7, and to case No. 1:

The explosion of a boiler of this form and of the proportions here given, in the year 1843, in the establishment of Messrs. R. L. Thurston & Co., at Providence, R. I., is well remembered by the Author. The boiler-house was entirely destroyed, the main building seriously damaged, and a large expense was incurred in the purchase of new tools to replace those destroyed. No lives were lost, as the explosion fortunately occurred after the workmen had left the building. A similar explosion of a boiler of this size occurred some years later, within sight of the Author, which drove one end of the exploding boiler through a 16-inch wall, and several hundred feet through the air, cutting off an elm tree high above the ground, where it measured 9 inches in diameter, partly destroying a house in its further flight, and fell in the street beyond, where it was found *red hot* immediately after striking the earth. Long after the Author reached the spot, although a heavy rain was falling, it was too hot to be touched, and was finally, nearly two hours later, cooled off by a stream of water from a hose, in order that it might be moved and inspected. It had been overheated, in consequence of low-water, and cold feed-water had then been turned into it. The boiler was in good order, but four years old, and was considered safe for 110 pounds. The attendant was seriously injured, and a pedestrian passing at the instant

of the explosion was buried in the ruins of the falling walls and killed. The energy of this explosion was very much less than that stored in the boiler when in regular work.

A boiler of class No. 3, which the Author was called upon to inspect after explosion, had formed one of a "battery" of ten or twelve, and was set next the outside boiler of the lot. Its explosion threw the latter entirely out of the boiler-house into an adjoining yard, displaced the boiler on the opposite side, and demolished the boiler-house completely. The exploding boiler was torn into many pieces. The shell was torn into a helical ribbon, which was unwound from end to end. The furnace-end of the boiler flew across the space in front of its house, tore down the side of a "kier-house," and demolished the kiers, nearly killing the kier-house attendant, who was standing between two kiers. The opposite end of the boiler was thrown through the air, describing a trajectory having an altitude of fifty feet, and a range of several hundred, doing much damage to property *en route*, finally landing in a neighboring field. The furnace-front was found by the Author on the top of a hill, a quarter of a mile, nearly, from the boiler-house. The attendant, who was on the top of the boiler at the instant of the explosion, opening a steam-connection to relieve the boiler, then containing an excess of steam and a deficiency of water, was thrown over the roof of the mill, and his body was picked up in the field on the other side, and carried away in a packing-box measuring about two feet on each side. The cause was low-water

HALLIDIE LIBRA

and consequent overheating, and the introduction of water without first hauling the fires and cooling down. Both this boiler and the plain cylinder are thus seen to have a projectile effect only to be compared to that of ordnance.

The violence of the explosion of the locomotive boiler is naturally most terrible, exceeding, as it does, that of ordnance fired with a charge of 150 pounds of powder of best quality, or perhaps 250 pounds of ordinary quality fired in the usual way.* On the occasion of such an explosion which the Author was called upon to investigate, in the course of his professional practice, the engine was hauling a train of coal cars weighing about 1000 tons. The steam had been shut off from the cylinders a few minutes before, as the train passed over the crest of an incline and started down the hill, and the throttle again opened a few moments before the explosion. The explosion killed the engineer, the fireman, and a brakeman, tore the fire-box to pieces, threw the engine from the track, turning it completely around, broke up the running parts of the machinery, and made very complete destruction of the whole engine. There was no indication, that the Author could detect, of low-water; and he attributed the accident to weakening of the fire-box sheets at the lower parts of the water-legs by corrosion. The bodies of the engineer and fireman were found several hundred feet from the wreck, the

* The theoretical effect of good gunpowder is about 500 foot-tons per pound (340 toum-metres per kilogramme), according to Noble and Able

former among the branches of a tree by the side of the track. This violence of projection of smaller masses would seem to indicate the concentration of the energy of the heat stored in the boiler, when converted into mechanical energy, upon the front of the boiler, and its application largely to the impulsion of adjacent bodies. The range of projection was, in one case, fully equal to the calculated range. The energy expended is here nearly the full amount calculated.

FIG. 37.—EXPLOSION OF BOILERS. BROOKLYN, N. Y.

Figures 37, 38, 39, 40 illustrate the explosion of two large boilers which produced very disastrous effects,*

* Scientific American, May 20, 1882.

killing the attendant and destroying the boiler-house and other property.

These boilers were horizontal, internally-fired, drop-flue boilers, seven feet diameter and twenty-one feet long, the shells, single riveted, originally five-sixteenths of an inch thick.

The two exploded boilers were made twenty-one years before the explosion, and worked, as their makers intended, at about thirty pounds per square inch, until about twenty months before the explosion, at which time additional power was required, and the pressure was increased to, and limited at, fifty pounds.

FIG. 38.—POSITION OF THE THREE BOILERS AFTER THE EXPLOSION.

A third boiler did not explode, but was thrown about fifty feet out of its bed.

A few minutes before noon, while the engine was running at the usual speed, the steam-gauge indicating forty-seven pounds pressure, and the water-gauges showing the usual amount of water, the middle one exploded;

the shell burst open and was nearly all stripped off. The remainder of the boiler was thrown high in the air.

While this boiler was in the air, No. 1, the left-hand boiler, having been forcibly struck by parts of No. 2, also gave way, so that its main portion was projected horizontally to the front, arriving at the front wall of the building in time to fall under No. 2, as shown in Fig. 38. The most probable method of rupture is indicated in Fig. 38, as the line *A B* separates a ring of plates which was found folded together beneath the pile of *débris*. If the initial break had been at some point on the bottom, this belt of plates would have been thrown upward and flattened, instead of downward, where it was folded by the flood of water from No. 1 boiler.

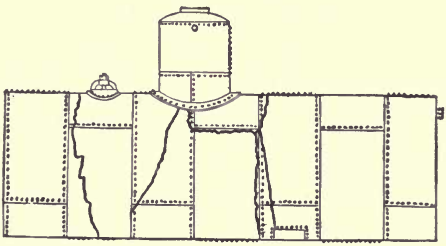


FIG. 39.—INITIAL RUPTURE.

The third boiler was raised from its bed by the issuing water, and thrown about fifty feet to the right of its original position.

These two boilers contained probably more than fourteen tons of water, which had a temperature due to forty-seven pounds of steam, and the effect of its sud-

den liberation equalled that of several hundred pounds of exploded gunpowder.

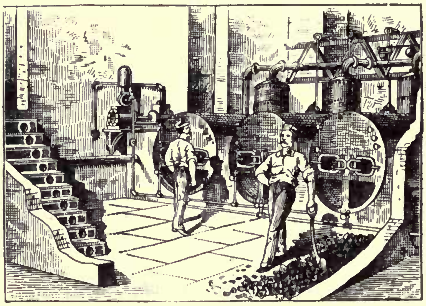


FIG. 40.—INTERIOR OF BOILER-HOUSE PRIOR TO EXPLOSION.

The terrible wreck usually consequent upon the explosion of a locomotive boiler is well illustrated in the

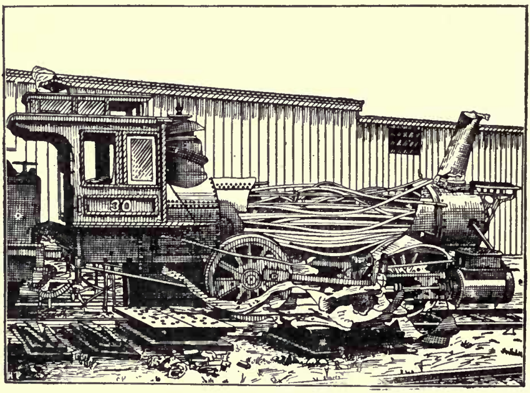


FIG. 41.—EXPLODED LOCOMOTIVE.

accompanying engraving, which represents the result of such an explosion on the Fitchburg railway, August 13,

1877, while the havoc wrought among the tubes on such an occasion is as strikingly illustrated in the next figure.

In the case of an explosion of a locomotive investigated by a commission of which the Author was a member, the train was moving slowly when the boiler exploded with a loud report; the locomotive was turned completely

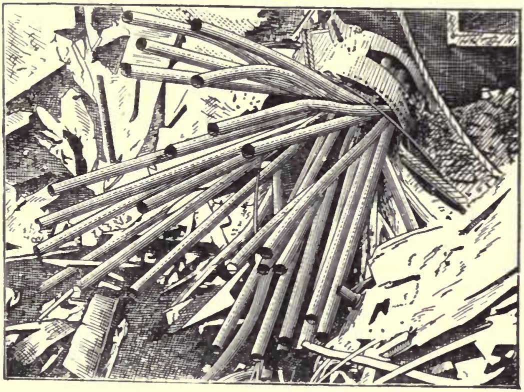


FIG. 42.—TUBES OF AN EXPLODED BOILER.

over backward, carrying with it the fireman, and burying him beneath the ruins.

Nothing could at first be found of the engineer. Parties searched for long distances about the wreck for signs of the unfortunate man, but it was not until next morning that his body was found. It was discovered lying in the woods, seven hundred feet away from the locomotive, which was completely demolished, and every part of the machinery was twisted or broken into pieces.

The track was torn up for some distance, and rails were bent like coils of rope.

The fire-box of the locomotive was hurled from its position and broken into many pieces. A large piece, weighing many hundred pounds, was carried 500 feet. The dome and sand-box were thrown an eighth of a mile into the adjacent river. The wheels of the engine were torn off, and not one piece of the cab was discovered. The engineer bore an excellent reputation as being a careful man, always carrying a large supply of water. The engine was one of approved make, and been in use for fifteen years. It had just come from the repair shop. A new fire-box had been put in three years before, and the boiler was thoroughly examined about six weeks earlier. The iron was, in many cases, twisted and bent into shapeless rolls. The point of rupture was apparently in the left hand lower corner of the outside shell of the fire-box. The cause was variously assigned as a percussive or "fulminating" action due to over-heated iron and to certain defective portions of the fire-box. The latter was probably the true cause.

The following may be taken as another illustration of the tremendous effects of explosion at usual working pressure with an ample supply of water. A boiler of the locomotive type was constructed for use in a small steamer. Its shell was of iron, 4 feet in diameter and 5-16th-inch thick. It was "tested" by filling with water and raising steam. It exploded with the safety-valve set at 120 pounds per square inch, blowing freely although held down by the man in charge, and killed

and injured several people. The hiss of steam escaping from the initial rupture was heard an instant before the explosion. The boiler was turned end for end, and the fire-box torn from the boiler in two pieces, one being carried to a distance of about five hundred feet and imbedded in the mud of a canal bed; the other portion, weighing about 4,800 pounds, was carried a distance of between 400 and 500 feet, and crashed into the side of a building, and with sash, blinds and doors, piled closely together. One piece of iron comprised the fire-box, the dome, and the end of the boiler, and was straightened into a piece 30 feet long and four feet wide. The piece is said to have rushed through the air with a whirling motion until it struck the building. It cut the side of the building and beams and rafters like straws, pushing the front of the building forward several feet. Fragments of the boiler were found at many points considerably distant from the scene of the explosion, and in many places windows were shattered by the concussion.

The shell of the boiler was reversed by the force of the explosion, with such force that one end was buried four feet in the road bed. All the flues remained in the boiler, one end of which was torn from them while the other remained in place.

At the instant of the explosion the air for many feet in every direction was filled with flying fragments, many of them being thrown to a great height.

In one case coming under the observation of the Author, a locomotive set as a stationary boiler gave way in the fire-box, and let out the water and steam, but in-

juring no one. The rent was about twelve inches long and eight inches wide. The iron in that place was weakened by corrosion, otherwise the boiler was in good condition. Repairs were immediately commenced and the boiler was ready for use next day. Had this rent occurred at or above the water-level, it is very possible that an explosion may have resulted in the manner suggested by Clark and Colburn.

In an explosion of a tubular boiler at Dayton, O., October 25th, 1881,* by which several lives and much property were destroyed, the rupture started along the lap *A B* in the figure, and was evidently due to the

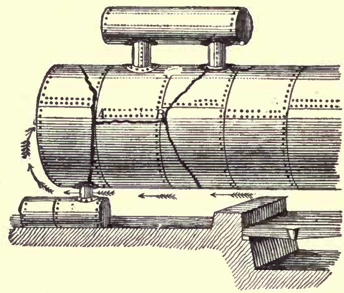


FIG. 43.—INITIAL RUPTURE; "GROOVING."

furrowing which had been there, in some way, produced. The boiler was less than a year old, and was reported to be of good material and workmanship. The longitudinal seams were double-riveted, and it is very possible that the stiffness thus produced along their lines may have so localized the strains due to alterations of

* Scientific American, Dec. 17th, 1881.

form as to have led to this fatal result, aided by the action of the caulking tool, the marks of which, along the lines at which the crack gradually worked through

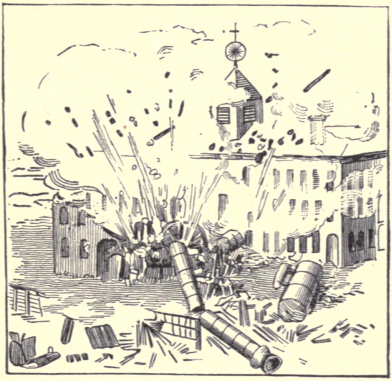


FIG. 44.—BOILER EXPLOSION AT DAYTON, OHIO.

the sheet, are plainly visible. The boiler had, when first set in place, been tested to 140 pounds; the explosion occurred at probably less than 80.

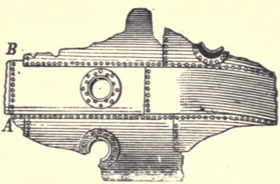


FIG. 45.—GIRDLE OF PLATES FROM NO. 2 BOILER.

A strip of plates, as in the above figure, was torn from the boiler, separating it into two parts, as seen in

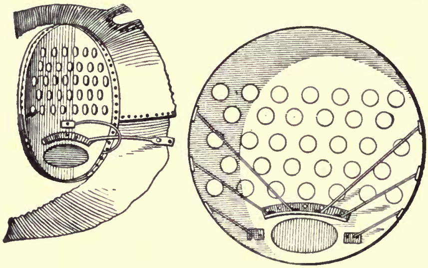


FIG. 46.—REAR END OF BOILER AFTER EXPLOSION. REAR END OF BOILER BEFORE EXPLOSION.

the two succeeding figures, and throwing them apart

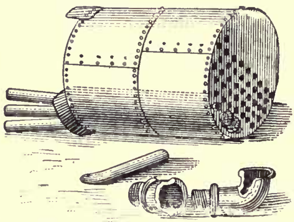
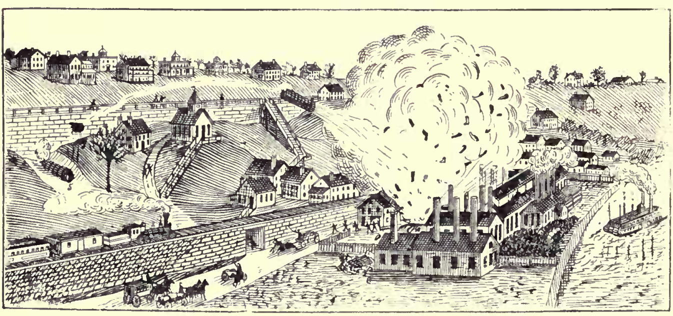


FIG. 47.—FRONT END OF BOILER AFTER EXPLOSION.

with all the force due to a hundred millions of foot-



5.—Principal part of No. 5 boiler thrown over the church on the bluff.
6.—Principal part of No. 6 boiler.
FIG. 48.—EXPLOSION OF TWO STEAM BOILERS AT PITTSBURG, PA.

pounds of available stored heat-energy, entirely destroying the house in which they were set.

In a case of explosion at Pittsburg, Pa., in December, 1881, a battery of flue-boilers was connected, as seen in the figure, by steam-drums above the nearer two and

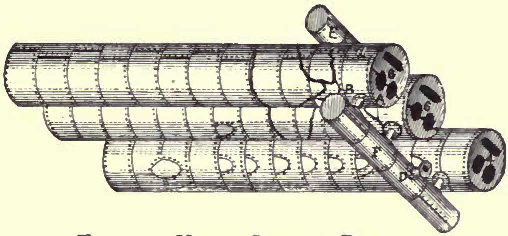


FIG. 49.—UNDER SIDES OF BOILERS.

mud-drums beneath all three. The steam-pressure was not far from 125 pounds per square inch at the time of the accident. The boilers were fifteen years old, but had been tested to 170 pounds two years earlier, and allowed to work at 120 pounds, although they had been repeatedly patched and repaired.* The rules of the insurance companies would have allowed but one-half this pressure.

The strains produced by the changes of form with varying temperature of feed-water, and by the action of the new iron of the patches on the older and corroded parts of the boilers, started cracks which gradually weakened them, and finally led to a rupture along the worst line of injury, *A B*, in the preceding figure, opening the course of plates at *a*, and tearing it out as in

* Scientific American, Feb. 4, 1882.

the next figure, in which *A B* is the line of initial fracture. The destruction of this (No. 6) boiler was accompanied by the disruption of that next to it (No. 5), which was also in about as dangerous condition. The available energy of the explosion was about 250,000,000

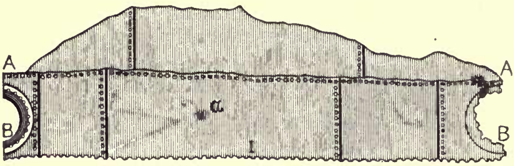


FIG. 50.—COURSE OF PLATES DETACHED.

foot-pounds, and the damage produced was proportioned to this enormous power.

One boiler (No. 5) was thrown across the road and over a church; the other (No. 6) was thrown to one

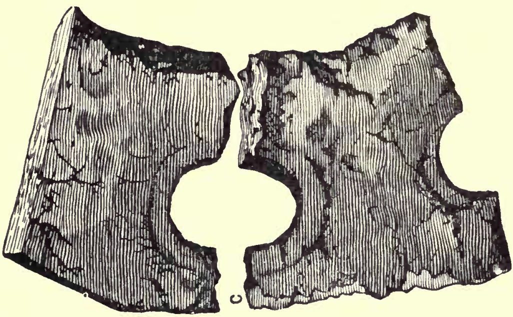


FIG. 51.—PIECE OF "PATCH."

side, partially destroying neighboring buildings. The boiler-house was entirely destroyed. The third boiler remained unexploded and was found a little out of place and nearly full of water.

According to the observer furnishing these particulars, the conclusions are inevitable:

That the two boilers exploded in succession so quickly as to be practically simultaneous, beginning at the weak line *A B* of No. 6 boiler;

That they contained an ample supply of water;

That the pressure was too great for boilers of their size and condition.

That the use of cold feed-water hastened the deterioration of poor iron, causing cracks and leaks, by which external corrosion was produced, and that the energy stored in the water of these boilers caused all the destruction observed.

It is always to be strongly recommended that regular and continuous feeding of hot water be practiced; and that the greatest care be exercised by inspectors and those in charge of steam-boilers in searching for and immediately repairing dangerous defects.

The last figure, preceding, is an excellent illustration of the appearance of iron when thus corroded. At *C*, the crack was old and partly filled up with lime scale.

The explosion of the upright tubular-boiler is usually consequent upon some injury of its furnace, either by collapse or by the yielding of the tube-sheet to excessive pressure. The result is commonly the projection of the boiler upward like a rocket, and is rarely accompanied by much destruction of property laterally. A typical case of this kind is that of an explosion occurring at Norwich, Connecticut, December 23, 1881, of which the following is a brief account:*

* Scientific American, Jan. 14, 1882.

FIG. 52.—EXPLOSION OF AN UPRIGHT BOILER.

Fig. 53 represents the location of the boiler and engine immediately before the explosion. The explosion took place, as shown in figure by the yielding of the lower tube plate of the boiler.

This boiler was three feet in diameter and seven feet high. The boiler was made of five-sixteenths iron throughout. It contained sixty tubes, two inches diameter, five feet long, which were set with a Prosser expander, and were beaded over as usual. The upper tube-head was flush with the top of the shell, and the lower, forming the crown of the furnace, was about two feet above the grates and the base of the shell, and was flanged upon the inner surface of the furnace. There was a safety plug in the lower tube-head, which was not melted out, although, as is often the case when these plugs are

so near the fire, a portion of the lower part of the fusible filling had disappeared.

FIG. 53.—THE BOILER ROOM BEFORE THE EXPLOSION.

The working pressure was sixty pounds per square inch, and the explosion probably took place at or a little

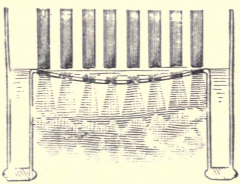


FIG. 54.—YIELDING TUBE SHEET.

below this pressure, throwing the boiler through the roof and high over a group of buildings and a tall tree close

by, finally burying itself half its diameter in the frozen ground.

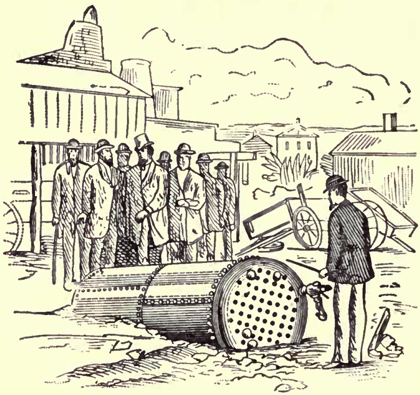


FIG. 55.—THE EXPLODED BOILER.

There had been leaks in the tubes and four had been plugged. There was a crack in the upper head near the center which extended between three tubes. From this crack steam escaped, and the water had settled upon the surrounding surface of the tube-head and the tube-ends. The result was to reduce the five-sixteenths plate to less than a quarter of an inch in thickness, and the tube-ends to the thickness of writing paper. The lower tube-ends had suffered still more from leaks and were as thin as paper and afforded no adequate support to the head. The pressure consequently forced the lower head down, opening fifty or more holes, two inches diameter, from which the fluid contents of the boiler issued at a high velocity, and the whole boiler became a great rocket weighing about two thousand pounds.

One life was destroyed by this explosion and a considerable amount of property.

An explosion which occurred at Jersey City, N. J., some years ago, illustrated at once the dangers of low-water and of a safety-valve rusted fast. As reported at the time:* "The boiler was of the locomotive type, having a dome upon the top. The engineer upon the

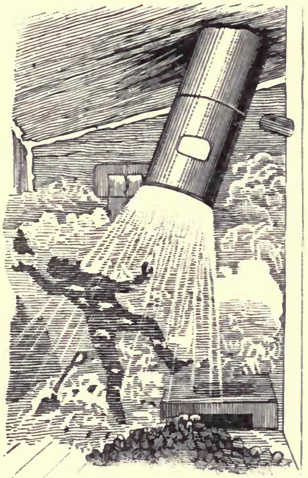


FIG. 56.—THE EXPLOSION.

morning of the explosion lighted the fire in the boiler and shortly afterward was called away, leaving the boiler in charge of his nephew, who was young and inexperienced in the handling of steam. After putting fresh coal in the furnace he was called away by one of the owners of the dock to assist at some outside duty. Upon his re-

* Am. Machinist, Oct. 1st, 1881.

turn he saw the seams of the boiler opening, and attempted to open the furnace door, but was unable, owing to the excess of pressure of steam within the boiler which had caused the head to change its shape. A few moments afterward the explosion occurred. The fire-box being thrown downward, the top of the shell and crown-sheet upward, while the cylinder part shot directly up the street. It struck the ground about 400 feet from its original position, demolished a fire hydrant, several trucks, trees, and a horse, and, spinning end for end, came to rest by the side of a truck, which it destroyed, about 642 feet from its starting point. Subsequent investigation revealed the fact that the boiler was not properly supplied with water. A portion of the crown sheet which we examined showed conclusively that near the flues it was red-hot. We also examined the safety-valve, which was of the wing pattern, having a lever and weight. This valve was so firmly corroded to its seat that it could not be removed, and the stem was also corroded fast. The whole secret of this explosion is that the boiler was short of water and an excessively high pressure of steam was raised to an unknown point; which, without relief, acquiring sufficient force, tore the boiler to pieces."

The valve was found and, being placed in a testing machine then under the charge of the Author, at the Stevens Institute of Technology, was only started by a pressure of a ton and a half; * while nearly two tons was required to move it observably.

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* Ibid, Oct. 22d, 1881.

Change of form with varying pressures and temperatures sometimes produces most unexpected defects. It

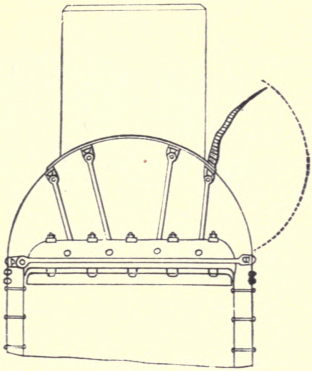

FIG. 57.—FAULTY STAYING.

has been observed that many locomotive boilers stayed as in the figure, * give way at the side, in the manner here exhibited. Investigation shows that, in these cases, the tying of the furnace-crowns to the shell by the system of staying illustrated, and the continual rising and falling of the furnace relatively to the shell, is very apt to cause a buckling of the outside sheet along the horizontal seam, which finally yields. This buckling and straightening of the sheet goes on until a crack or a furrow is formed along the lap nearest the most rigid brace, and, when this has cut deeply enough, the side of the boiler opens, often the whole length of the furnace, the explosion doing an amount of damage which is determined

* Locomotive, Jan. 1, 1880.

by the steam pressure, the quantity of energy stored, and the extent of the rupture.

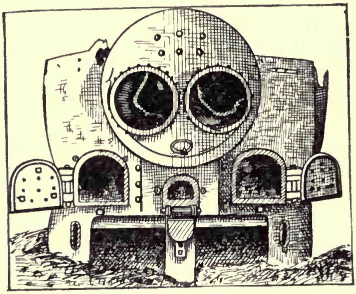

FIG. 58.—COLLAPSED FLUES.

In these cases, either the crown-bars over the furnace, or the stays, should alone have been used; their use to-

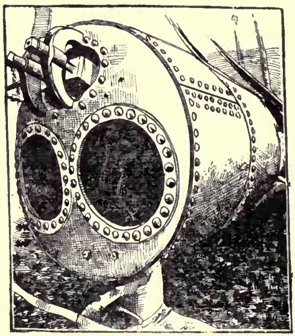

FIG. 59.—COLLAPSED FLUES.

gether is objectionable. Of the two systems, probably the first is safest in such boilers.

The appearance of a collapsed flue is seen in the two

succeeding figures, which represent the results of experiments made by the U. S. Commission appointed to investigate the causes of explosions of steam boilers. In neither case did the boiler move far from its original position. Collapsed flues rarely cause extensive destruction of property.

An explosion of a rotary rag-boiler, receiving steam from steam-boilers at a distance, which took place at Paterson, N. J., wrecked the mill, destroyed a part of an adjacent establishment, and caused serious loss of life and property. The disaster was due to the weakening of the boiler by corrosion, but, notwithstanding its reduced strength, the shock of the explosion was felt, and was heard, throughout the city, and heavy plate-glass windows were broken at a considerable distance from the scene of the accident. Explosions of this kind show the fallacy of many of the absurd and mischievous "theories" which have been prevalent in regard to explosions.

Where the iron or steel used in the construction of the boiler is of good quality, strong, uniform and ductile, the smaller torn parts of an exploded boiler may not break away from the main body; such a case is illustrated in the accompanying figure, which represents the effect of an explosion of a new boiler from a cause not ascertained.

The boiler was 15 feet long by 4 feet diameter, with 38 four-inch flues. Both heads remained on the flues, but the shell of the boiler burst along the rivet-holes nearly all around both heads, as shown in the engraving.

32. **Experimental Investigations** of the causes and methods of steam-boiler explosions have been occasionally attempted. One of the earliest and most syste-

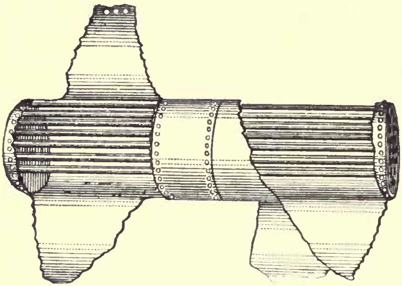

FIG. 60.—AN EXPLODED BOILER.

matic, as well as fruitful, was that of a Committee of the Franklin Institute, the results of which were reported to the Secretary of the U. S. Treasury, early in 1836.

Unpublished experiments recently made by Professor Mason at the Rensselaer Polytechnic Institute, strongly confirm the so-called "geyser theory" of Messrs. Clark and Colburn. In these experiments a number of miniature boilers were constructed, and were exploded by a gradually produced excess of pressure, and in such manner as to test this theory. The first of these boilers, when exploded, produced such an effect, blowing out windows and shaking down the ceiling of the laboratory as effectually to dispose of the idea prevalent among certain classes of engineers, that a true explosion could only be caused by low-water and overheated plates. Another boiler was so set that, the rear end being lower than the front, the quantity of water acting by percus-

sion, according to the Clark theory, was much greater at the one end than at the other. The consequence was that, while the one end was broken into many pieces, that in which there was least water was simply torn from the mass of the boiler and was itself unbroken. In one of this series of experiments the boiler was broken into more than a hundred pieces, although made of drawn brass, a material far less liable, ordinarily, to be thus shattered than iron or steel. The second of the above described experiments appears to the Author a very nearly crucial test and proof of the theory of Messrs. Clark and Colburn.

The Franklin Institute committee proposed by experiments :

(I). To ascertain whether, on relieving water heated to, or above, the boiling point, from pressure, any commotion is produced in the fluid.

To determine the value of glass gauges and gauge-cocks.

The investigation of the question whether the elasticity of steam within a boiler may be increased by the projection of foam upon the heated sides, more than it is diminished by the openings made.

(II). To repeat the experiments of Klaproth on the conversion of water into steam by highly heated metal and to make others, calculated to show whether, under any other circumstances, intensely heated metal can produce, suddenly, great quantities of highly elastic steam.

To directly experiment in relation to the production

of highly elastic steam in a boiler heated to high temperature.

(III). To ascertain whether intensely heated and unsaturated steam can, by the projection of water into it, produce highly elastic vapor.

(IV). When the steam surcharged with heat is produced in a boiler, and is in contact with water, does it remain surcharged, or change its density and temperature?

(V). To test, by experiment, the efficacy of plates, etc., of fusible metal, as a means of preventing the undue heating of a boiler, or its contents.

(1). Ordinary fusible plates and plugs.

(2). Fusible metal, inclosed in tubes.

(3). Tables of the fusing points of certain alloys.

(VI). To repeat the experiments of Klaproth, &c.

(1). Temperature of maximum vaporization of copper and iron under different circumstances.

(2). The extension to practice, by the introduction of different quantities of water, under different circumstances of the metals.

(VII). To determine by actual experiment, whether any permanently elastic fluids are produced within a boiler when the metal becomes intensely heated.

(VIII). To observe accurately the sort of bursting produced by a gradual increase of pressure, with cylinders of iron and copper.

(IX). To repeat Perkins' experiment and ascertain whether the repulsion stated by him to exist between the particles of intensely heated iron and steam be gen-

eral, and to measure, if possible, the extent of this repulsion, with a view to determine the influence it may have on safety-valves.

(X). To ascertain whether cases may really occur when the safety-valve, loaded with a certain weight, remains stationary, while the confined steam acquires a higher elastic force than that which would, from calculation, appear necessary to overcome the weight of the valves.

(XI). To ascertain by experiment the effects of deposits in boilers.

(XII). Investigation of the relation of temperature and pressure of steam, at ordinary working pressures.

It is only necessary here to state that the result proved:

(1). That relieving pressure, even slightly, produced great commotion in the water, and considerably relieving it caused the violent ejection of water as well as steam through the opening by which the pressure was reduced.

(2). That under similar conditions pressure invariably diminished.

(3). That the injection of water upon the heated surfaces of the experimental boiler, produced a sudden and considerable rise of pressure.

(4). That the injection of water into superheated steam reduced its pressure.

(5). That superheated steam may remain in contact with water a long time (two hours in the experiments tried), without becoming saturated.

(6). That fusible plugs, as then constructed, were unreliable. The fusing point of various alloys were determined.

(7). That the temperature of maximum vaporization of water is lowered by smoothness of surfaces; that that of iron is thirty or forty degrees higher than that of copper, while the time required is one-half as great with copper; that the temperature of maximum vaporization, for oxidized iron, or for highly oxidized copper is about 350° F., and that the repulsion between the metal and the water is perfect at from twenty to forty degrees above the temperature of maximum vaporization.

(8). That no hydrogen is liberated by throwing water or steam upon heated surfaces of the boiler; that the water was not decomposed, and that air cannot occur in any appreciable quantity in a steam-boiler at work.

(9). That "*all the circumstances attending the most violent explosions may occur without a sudden increase of pressure within a boiler*," the explosion being produced by gradually accumulated pressure.

(10). That but a small portion of water, highly heated, can expand into steam, if suddenly relieved of pressure.

(11). That water can be heated to very high temperature only under immensely high pressure.

(12). That steam-pressure may rise even after it has raised the safety-valve.

Over thirty years passed before another serious attempt was made to thoroughly investigate the subject;

but in the year 1871, experiments were inaugurated on a large scale.*

In the work of investigation involving the explosion of steam-boilers, it is usually necessary to provide a safe retreat for the observers, from which to watch the progress of the experiment, and from which to read the steam-gauge, to watch the water-level, and to take the reading of the thermometers or pyrometers.

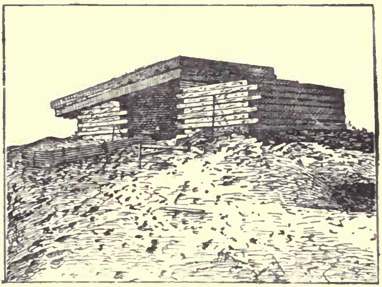

FIG. 61.—BOMB-PROOF.

The illustration represents the structure, composed of heavy timber, and partially underground, used at the testing ground at Sandy Hook, by the U. S. Commission of 1873-6.

These experiments were projected and conducted by Mr. Francis B. Stevens, of Hoboken, and at the request of Mr. S. the United Railroad Companies of New Jersey appropriated the sum of ten thousand dollars to enable Mr. Stevens to enter upon a preliminary series of ex-

* Journal Franklin Inst., Jan., 1872.

periments. They, at the same time, invited other railroads and owners of steam-boilers to co-operate with them, and offered the use of their shops for any work that might be considered necessary or desirable during the progress of the work; no such aid was, however, received.

Several old boilers had recently been taken out of the steamers of the United Companies. These were subjected to hydrostatic pressure, until rupture occurred, were repaired and again ruptured several times each, thus detecting and strengthening their weakest spots, and finally leaving them much stronger than when taken from the boats. The points at which fracture occurred and the character of the break were noted carefully at each trial.

After the weak spots had thus been felt out and strengthened, the boilers were taken, with the permission of the War Department, to the U. S. reservation at Sandy Hook, at the entrance to New York Harbor, and were there set up in a large enclosure which had been prepared to receive them, and the four old steamboat boilers above referred to, together with five new boilers built for the occasion, were placed in their respective positions without having been in any way injured.

Finally, on the 22d and 23d of November, the experiments to be described were made.

The first boiler attacked was an ordinary "single return flue boiler."

The cylindrical portion of the shell was 6 feet 6 inches diameter, 20 feet 4 inches long, and of iron a full quarter

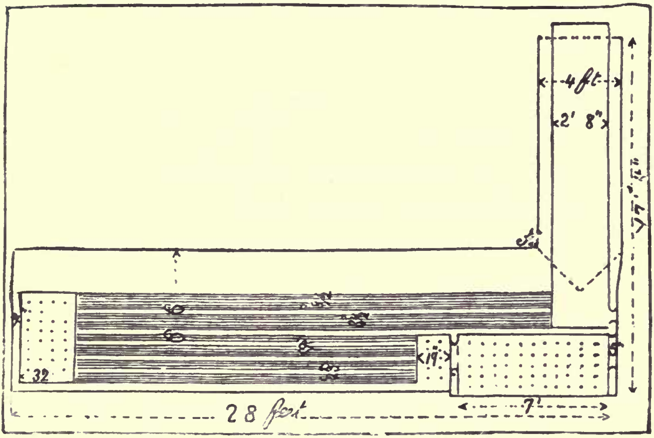

FIG. 62.—MARINE BOILER.

inch thick. The total length of the boiler was 28 feet, the steam chimney was 4 feet diameter, 10½ feet high, and its flue was 32 inches diameter. The two furnaces were 7 feet long, with flat arches. There were ten lower flues, two of 16 and eight of 9 inches diameter, and all were 15 feet 9 inches long; there were twelve upper flues, 8½ inches in diameter, and 22 feet long. The total grate surface was 38½ square feet, heating surface 1350 square feet. The water spaces were 4 inches wide, and the flat surfaces were stayed by screw stay-bolts at intervals of 7 inches. The boiler was thirteen years old, and had been allowed 40 pounds pressure.

The upper portion of the boiler, when inspected before the experiment, seemed to be in good order. The girth

seams on the under side of the cylindrical portion had given way, and had all been patched before it was taken out of the boat. The water legs had been considerably corroded.

In September this boiler had been subjected to hydrostatic pressure, giving way by the pulling through of stay-bolts at 66 pounds per square inch. It was repaired and, afterward, at Sandy Hook, was tested without fracture to 82 pounds, and still later bore a steam pressure of 60 pounds per square inch.

On its final trial, Nov. 22d, a heavy wood fire was built in the furnaces, the water standing 12 inches deep over the flues, and, when steam began to rise above 50 pounds, the whole party retired to the gauges, which were placed about 250 feet from the enclosure. The notes of pressures and times were taken as follows:

Time.	Pressure.	Time.	Pressure.	Time.	Pressure.	Time.	Pressure.
2.00 P.M.	58 lbs.	2.15 P.M.	87 lbs.	2.25 P.M.	91½ lbs.	2.40 P.M.	91½ lbs.
2.05 "	68 "	2.20 "	91½ "	2.36 "	91 "	2.45 "	91 "
2.10 "	78 "	2.23 "	93 "	2.35 "	91½ "	2.50 "	90 "

The pressure rose rapidly until it reached about 90 pounds,* when leaks began to appear in all parts of the boiler, and at 93 pounds a rent at A, (Fig. 62) the lower part of the steam chimney where it joins the shell becoming quite considerable, and other leaks of less extent en-

* The ultimate strength of this boiler, when new, was probably equal to about double this pressure.

larging, the steam passed off more rapidly than it was formed. The pressure then slowly diminishing, the workmen extinguished the fires by throwing earth upon them, and the experiment thus ended.

The second experiment was made with a small boiler

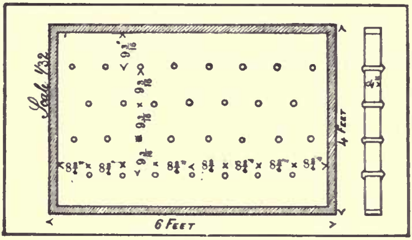

FIG. 63.—STAYED WATER SPACE.

(Figure 63) which had been constructed to determine the probable strength of the stayed-surface of a marine boiler. It had the form of a square box, 6 feet long, 4 feet high, and 4 inches thick. Its sides were 5 inch thick, of the "best flange fire-box" iron. The water-space was 3⅜ inches wide. The rivets along the edges were ¾ inch diameter, spaced 2 inches apart. The two sides were held tegether by screw stay-bolts, spaced 8¾ and $9\frac{3}{16}$ inches, and their ends were slightly riveted over, precisely copying the distribution and workmanship of a water-leg of an ordinary marine boiler It had been tested to 138 lbs. pressure. This slab was set in brickwork, about five-sixths of its capacity occupied by water, and fires built on both sides. Pressure rose as shown by the following extract from the note-book of the Author:

Time.	Pressure.	Time.	Pressure.	Time.	Pressure.	Time.	Pressure.
3.18 P.M.	0 lbs.	3.27 P.M.	18 lbs.	3.35 P.M.	49 lbs.	3.43 P.M.	94 lbs.
3.20 "	4 "	3.28 "	20 "	3.36 "	51 "	3.44 "	100 "
3.21 "	5 "	3.29 "	23 "	3.37 "	54 "	3.45 "	110 "
3.22 "	7 "	3.30 "	27 "	3.38 "	58 "	3.46 "	117 "
3.23 "	9 "	3.31 "	30 "	3.39 "	65 "	3.47 "	126 "
3.24 "	11 "	3.32 "	34 "	3.40 "	72 "	3.48 "	135 "
3.25 "	13 "	3.33 "	38 "	3.41 "	78 "	3.49 "	147 "
3.26 "	15 "	3.34 "	44 "	3.42 "	86 "	3.50 "	160 "
						3.51 "	165 "
						Exploded.	

At a pressure of slightly above 165, and probably at about 167 pounds, a violent explosion took place. The brickwork of the furnace was thrown in every direction, a portion of it rising high in the air and falling among the spectators near the gauges; the sides of the exploded vessel were thrown in opposite directions with immense force, one of them tearing down the high fence at one side of the enclosure, and falling at a considerable distance away in the adjacent field; the other part struck one of the large boilers near it, cutting a large hole, and thence glanced off, falling a short distance beyond.

Both sides were stretched very considerably, assuming a dished form of 8 or 9 inches depth, and all of the stay-bolts drew out of the sheets without fracture and without stripping the thread of either the external or the internal screw; this effect was due partly to the great extension of the metal, which enlarged the holes, and partly to the rolling out of the metal as the bolts drew from their sockets in the sheet.

Lines of uniform extension seemed to be indicated by a peculiar set of curved lines cutting the surface scale of oxide on the inner surface of each sheet, and resembling

closely the lines of magnetic force called, by physicists, magnetic spectra. These curious markings surrounded all of the stay-bolt holes.

The third experiment took place on the 23d of November. The boiler selected on this occasion was a "return tubular-boiler," with no lower flues; the furnace and combustion-chamber occupying the whole lower part. Its surface extended the whole width of the boiler, thus giving an immense crown-sheet.

This boiler was built in 1845, and had been at work *twenty-five years;* when taken out, the inspector's certificate allowed 30 lbs. of steam. In September it was subjected to hydrostatic pressure, which at 42 pounds broke a brace in the crown-sheet, and at 60 pounds, 12 of the braces over the furnace gave way, and allowed so free an escape of water as to prevent the attainment of a higher pressure. The broken parts were carefully repaired, and the boiler again tested at Sandy Hook to 59 lbs., which was borne without injury, and afterward a steam-pressure of 45 lbs. left it still uninjured. At the final experiment, the water level was raised to the height of 15 inches above the tubes, and it there remained to the end. The fire was built, as in the previous experiments, with as much wood as would burn freely in the furnace, and the record of pressures was as follows:

Time.	Pressure.	Time.	Pressure.	Time.	Pressure.
12.21 P.M.	29½ lbs.	12 27 P.M.	41 lbs.	12.32 P.M.	50 lbs., brace broke.
12.23 "	33½ "	12.29 "	44½ "	12.33 "	52 "
12.25 "	37½ "	12.31 "	48½ "	12.34 "	53½ " exploded.

In these second and third experiments, we have illustrations of the comparatively rare cases in which explosions actually occur.

The second was a perfectly new construction, in which corrosion had not developed a point of great comparative weakness, and the edges yielding along the lines of riveting on all sides simultaneously and very equally, the two halves were completely separated, and thrown far apart with all of the energy of unmistakable explosion, although there was an ample supply of water, and the pressure did not exceed that frequently reached in locomotives and on the western rivers, and although the boiler itself was quite diminutive.

In the third experiment, as in the second, it is probable that the weakest part extended very uniformly over a large part of the boiler, either in lines of weakened metal, or over surfaces largely acted upon by corrosion. Immediately upon the giving way of its braces, fracture took place at once in many different parts.

33. **Conclusion.** We may conclude, then, from the result of Mr. Stevens' experiments:

First.—That "low-water," although undoubtedly one cause, is not the only cause of violent explosions, as is so commonly supposed, but that a most violent explosion may occur with a boiler well supplied with water, and in which the steam-pressure is gradually and slowly accumulated.

This was shown on a small scale by the experiments of the Committee of the Franklin Institute above referred to.

Second.—That what is generally considered a moderate steam-pressure may produce the very violent explosion of a weak boiler, containing a large body of water, and having all its flues well covered.

This had never before been directly proven by experiment.

Third.—That a steam-boiler may explode, under steam, at a pressure less than that which it had successfully withstood at the hydrostatic test.

The last boiler had been tested to 59 lbs., and afterward exploded at 53½ lbs. This fact, too, although frequently urged by some engineers, was generally disbelieved. It was here directly proven.*

In addition to the deductions summarized above, the Author would conclude:

Fourth.—That the violence of an explosion under gradually accumulating pressures is determined largely by the nature of the injury and the extent of the primary rupture due to it. A merely local defect or failure would not be likely to cause explosion.

---

* A number of instances of this kind, though not always producing an explosion, have been made known to the Author. Two boilers at the Detroit Water Works, in 1859, after resisting the hydrostatic test of 200 lbs. with water, at a temperature of 100° Fahr., broke several braces each at 110 and 115 lbs. steam pressure respectively, when first tried under steam. The boiler of the U. S. steamer Algonquin was tested with 150 lbs. cold water-pressure, and broke a brace at 100 lbs. when tried with steam. A similar case occurred in New York, a few years ago, and the boiler exploded with fatal results. These accidents are probably caused by the changes of form of the boiler, under varying temperature, which throw undue strain upon some one part, which may have already been nearly fractured.

Fifth.—That the overheating of the metal of a boiler in consequence of low-water may, or may not, produce explosion, accordingly as the sheet is more or less weakened, or as the amount of steam made on the overflow of the dry heated area by water is greater or less.

Sixth.—That the superheating of either water or steam is not to be considered a probable cause of explosion.

Seventh.—That the question whether the repulsion of water from a plate by the overheating of the latter may occur with resulting explosion remains unsettled, but that it is certain that the number of explosions attributable to this cause is comparatively small.

Eighth.—That all explosions are certainly due to simple and preventable causes, and nearly all to simple ignorance or carelessness, on the part of either designer, constructor, proprietor, or attendants.

A Committee of the British House of Commons after long study and careful investigation of this subject, made the following recommendations:

" 13. (*a*) That it be distinctly laid down by statute that the steam-user is responsible for the efficiency of his boilers and machinery, and for employing competent men to work them; (*b*) that, in the event of an explosion, the onus of proof of efficiency should rest on the steam-user; (*c*) that in order to raise *prima facie* proof, it shall be sufficient to show that the boiler was at the time of the explosion under the management of the owner or user, or his servant, and such *prima facie* proof shall only be rebutted by proof that the accident

arose from some cause beyond the control of such owner or user; and that it shall be no defence in an action by a servant against such owner or user being his master, that the damage arose from the negligence of a fellow servant."

The Prevention of steam-boiler explosions is now seen to be a matter of the utmost simplicity. A well designed, well made and set, and properly managed steam-boiler may be considered as safe. Explosions rarely occur in such cases. To secure correct design and proportions, a competent engineer should be found to make the plans; to obtain good construction, a reliable, intelligent and experienced maker must be entrusted with the construction under proper supervision and precise instructions from the designer; and the latter should also attend carefully to the installation of the boiler. In order to insure good management, trustworthy, skillful, and experienced attendants must be found, who, under definite instructions, may at all times be depended upon to do their work properly. Periodical inspection, prompt repair of all defects when discovered, and the removal of the boiler before it has become generally deteriorated and unreliable, are the best safeguards against explosion.

This inspection should be made by, or in accordance with, the best methods of reputable insurance and inspection companies, by an expert of recognized competence and experience. It should include both internal and external inspection of every part and no part

should be permitted to be inaccessible for such inspection. If such part is thus necessarily neglected, it may reasonably be expected that a catastrophe may have origin at that point.

This inspection should be accompanied by "hammer-test" of parts known to be liable to deterioration and should usually be followed by a test under hydraulic pressure to determine the safety of the structure as a whole. The concealed laps of shell-boiler seams and the stays of locomotive boilers are peculiarly liable to failure, and should therefore be most carefully watched.

Wrought iron has now been practically superseded by steel in boiler-work, and the homogeneousness and reliability of the metal add greatly to the security of the structure.

The following are comparative records of railroad accidents and boiler explosions.*

RAILWAY ACCIDENTS, JAN., FEB., AND MARCH, 1902.

Character of Accidents.	Number of Accidents.	Passengers.		Employés.	
		Killed.	Injured.	Killed.	Injured.
Collisions.......	1,220	26	501	104	763
Derailments.....	838	15	298	53	351
Totals	2,058	41	799	157	1,114

* The Locomotive, August, 1902.

BOILER EXPLOSIONS, JAN., FEB., AND MARCH, 1902.

Month.	Number of Explosions.	Persons Killed.	Persons Injured.
January....................	35	25	45
February..................	38	24	46
March......................	32	22	32
Totals.................	105	71	123

The very common form of explosion, especially with locomotives, due to low water and over-heated crown-sheets, may be avoided usually by proper use

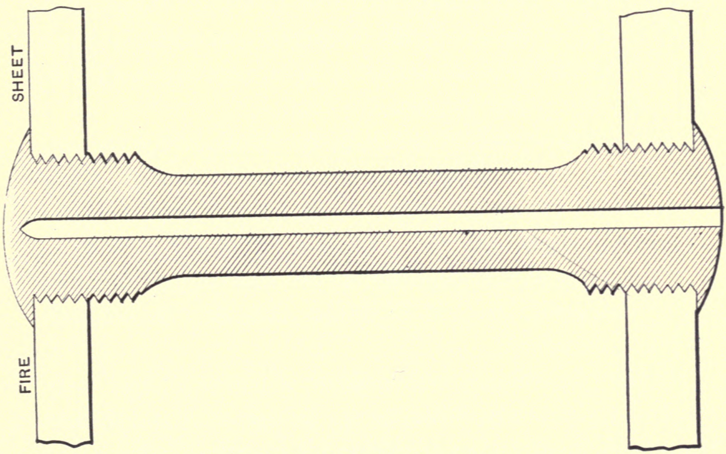

FIG. 63.—DRILLED STAYBOLT.

of good forms of fusible plugs. Their liability to failure to act when covered by incrustation or sediment may be reduced by proper inspection and care. They

should be renewed at intervals, as they are sometimes altered by long exposure to heat and rapid changes of temperature.

Staybolts should be similarly treated, renewing a portion at each inspection in such manner that none should be retained longer than about two years. Solid staybolts should be drilled axially to insure detection of faults before breakage takes place. "Flexible staybolts" are probably safest. The corrugated furnace evades this danger.

In construction, expansion and contraction should be carefully provided for. Bent sheets should have large radii of curvature.

A factor of safety of *five* is usually prescribed; but a larger figure will decrease danger initially and will prolong the working period.

Solid-drawn tubes can now be obtained for boilers, and are vastly preferable to lap-welded tubes.

In water-tube boilers particularly, thicker tubes are coming into use.

Danger from the presence of oil can only be evaded by its exclusion from the boiler. Alkalies in solution prevent corrosion.

Acid oils should never enter a boiler. The only other source of corrosion is air in the feed-water, and since the substitution of mineral for animal lubricating oils, this is the only cause of the "pitting" often occurring in all boilers, and especially in water-tube boilers. Alkaline water produces little or no corrosion in any case. Acid water may cause exceedingly serious injury.

Sea-water is ordinarily about twice as corrosive as pure water, and added mineral matter, as chlorides and sulphates, has greater effect in solution than with pure water.

Mr. F. J. Rowan, after a very extended review of the subject, sums up the case for prevention of destruction of boilers, especially marine, by explosion or otherwise, thus:

1. The metal of which boilers are constructed should be as homogeneous as possible in composition and texture. It should be well worked, so as to be fibrous rather than crystalline in texture, and should not be punched or worked at a low heat. It should be well annealed, so as to remove all effects of local stresses, and to bring the texture to a uniform condition.

2. All mill scale and dirt should be removed from the surfaces, which should also be kept as free as possible from oil.

3. All gases should be removed from the water.

4. No sea-water should be admitted, and all feed-water should be made up with distilled water.

5. All feed-water should be passed through a good filter.

6. The feed-water should be heated in feed-heaters which are separate in construction from the boiler.

7. The interior surfaces of the boiler should be covered by a thin protective coating or the water should be treated chemically.

8. No vegetable or animal oil should be used in any engines connected in any way with the boiler.

9. When not in use boilers should be carefully protected from deterioration.

APPENDIX.

SEDIMENT COLLECTING IN A STEAM-BOILER

Evaporating 1,000 Gallons of Water per Day, and 6,000 Gallons per Week. (Engelhart.)

When a Gallon of Feed-water, Evaporated to Dryness at 212°, Leaves Solid Matter in Grains,	The Amount of Solid Matter Collecting in Boiler per Day will be		The Amount of Solid Matter Collecting in Boiler per Week will be		When a Gallon of Feed-water, Evaporated to Dryness at 212°, Leaves Solid Matter in Grains,	The Amount of Solid Matter Collecting in Boiler per Day will be		The Amount of Solid Matter Collecting in Boiler per Week will be	
	Lbs.	*Ounces.*	*Lbs.*	*Ounces.*		*Lbs.*	*Ounces.*	*Lbs.*	*Ounces.*
1 grain............	—	2.28	—	13.71	65 grains	9	4.57	55	11.42
2 grains...........	—	4.57	1	11.42	70 "	10	—	60	—
3 "	—	6.85	2	9.14	75 "	10	11.42	64	4.57
4 "	—	9.14	3	6.85	80 "	11	6.85	68	9.14
5 "	—	11.42	4	4.57	85 "	12	2.28	72	13.71
6 "	—	13.71	5	2.28	90 "	12	13.71	77	2.28
7 "	1	—	6	—	95 "	13	9.14	81	6.85
8 "	1	2.28	6	13.71	100 "	14	4.57	85	11.42
9 "	1	4.57	7	11.42	110 "	15	11.42	94	4.57
10 "	1	6.85	8	9.14	120 "	17	2.28	102	13.71
15 "	2	2.28	12	13.71	130 "	18	9.14	111	6.85
20 "	2	13.71	17	2.28	140 "	20	—	120	—
25 "	3	9.14	21	6.85	150 "	21	6.85	128	9.14
30 "	4	4.57	25	11.42	160 "	22	13.71	137	2.28
35 "	5	—	30	—	170 "	24	4.57	145	11.42
40 "	5	11.42	34	4.57	180 "	25	11.42	154	4.57
45 "	6	6.85	38	9.14	190 "	27	2.28	162	13.71
50 "	7	2.28	42	13.71	200 "	28	9.14	171	6.85
55 "	7	13.71	47	2.28	210 "	30	—	180	—
60 "	8	9.14	51	6.85					

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